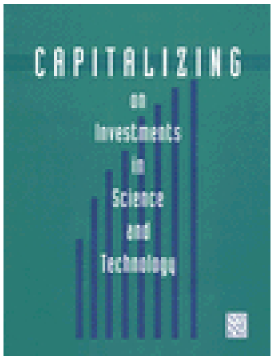

Capitalizing on Investments in Science and Technology

Committee on Science, Engineering, and Public Policy; National Academy of Sciences, National Academy of Engineering, and Institute of Medicine

ISBN: 0-309-52477-6, 128 pages, 8.5 x 11, (1999)

CAPITALIZING on Investments in Science and Technology

COMMITTEE ON SCIENCE, ENGINEERING, AND PUBLIC POLICY

National Academy of Sciences
National Academy of Engineering
Institute of Medicine

NATIONAL ACADEMY PRESS
Washington, D.C. 1999

National Academy Press • 2101 Constitution Ave., NW • Washington, DC 20418

NOTICE: This volume was produced as part of a project approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. It is a result of work done by the Committee on Science, Engineering, and Public Policy (COSEPUP) as augmented, which has authorized its release to the public. This report has been reviewed by a group other than the authors according to procedures approved by COSEPUP and the Report Review Committee. The development of this report was supported by the Alfred P. Sloan Foundation, the National Institutes of Health, and the National Research Council. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the organizations or agencies that provided support for the project.

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Library of Congress Catalog Card Number 99-61403

International Standard Book Number 0-309-06291-8

Printed in the United States of America

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PREFACE

This report explores how well the United States is capitalizing on its investments in science and engineering research, and how capitalization can be sustained and made more effective in the future. The study was undertaken during a period of intense debate over science and technology policy. The benefits of applying new knowledge are becoming more apparent in the economy and other areas of national life. At the same time, efforts are under way to extend this success to other pressing national needs, such as education. Because science, engineering, and patterns of capitalization are continually changing, improving U.S. ability to capitalize requires continued study, learning, and debate. We hope that this report contributes to the ongoing national discussion.

The production of the report was the result of hard work by the committee as a whole, and the extra effort of the working group consisting of Gerald Dinneen, Peter Diamond, Mildred Dresselhaus, M.R.C. Greenwood, J. Tomas Hexner, Daniel McFadden, Paul Romer, Morris Tanenbaum, William Julius Wilson, and me. Special thanks go to Gerald Dinneen, who chaired the working group.

This report has benefited from input from various individuals. COSEPUP acknowledges those who made presentations at the various workshops organized during the course of the study: Lawrence Rabiner, AT&T Bell Laboratories; Michael Cohen, Nuance Technologies and SRI International; Abeer Alwan, University of California, Los Angeles; David Mowery, University of California, Berkeley; Ashok Chandra, IBM Almaden Laboratory; Larry Smarr, University of Illinois; Richard Taylor, University of California, Irvine; Michael Cima, Massachusetts Institute of Technology; Eric Cross, Pennsylvania State University; Bharat Rawal, AVX Corp.; Steven Freiman, National Institute of Standards and Technology; Michael Butler, Sandia National Laboratory; John Woodward, YSI Inc.; William Spencer, SEMATECH; Adam Jaffe, Brandeis University; Richard Nelson, Columbia University; Edgar Haber, Harvard Medical School; Joshua Lerner, Harvard Business School; Alexis T. Bell, University of California, Berkeley; Mark E. Davis, California Institute of Technology; Brian L. Goodall, BFGoodrich; Barbara Knight Warren, Union Carbide; Dale Drueckhammer, Stanford University; Burton J. McMurtry, Technology Venture Investors; Jeffrey Sohl, University of New Hampshire; James F. Gibbons, Stanford University; Kenneth P. Morse, MIT Entrepreneurship Center; Philip Horsley, Horsley-Bridge Associates; William Melton, CyberCash; J. Leighton Read, Aviron Inc.; Charles Hsu, Walden Group of Venture Capital Funds; Jerome Grossman, HealthQuality Inc.; Catherine Ailes, SRI International; Frank Hughes, Boeing; Paula Stephan, Georgia State University; Bernard O. Palsson, University of California at San Diego; Carlos Zamudio, Axiom Biotechnologies; Stephen Clark, Amgen; Robert Sproull, Sun Microsystems; David

Farber, University of Pennsylvania; Deborah Estrin, University of Southern California; Brian Reid, Digital Equipment; Ralph Cavin, Semiconductor Research Corp.; James Plummer, Stanford University; and Donald Wollesen, Advanced Micro Devices.

This report has been reviewed by persons chosen for their diverse perspectives and technical expertise in accordance with procedures approved by the National Research Council's Report Review Committee. The purposes of this independent review are to provide candid and critical comments that will assist COSEPUP in making its report as sound as possible and to ensure that the report meets institutional standards of objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following for their participation in the review of this report: Erich Bloch, Kent Bowen, Alexander Flax, Robert Lucky, Ruben Mettler, Richard Nelson, Yoshio Nishi, Simon Ostrach, and Roland Schmitt. All those persons have provided many constructive comments and suggestions. Responsibility for the final content of this report rests solely with COSEPUP.

Phillip A. Griffiths
Chair
Committee on Science, Engineering, and Public Policy

CONTENTS

EXECUTIVE SUMMARY

In recent months there has been a surge of interest in the U.S. science and engineering enterprise and its contribution to national well-being. Several prestigious groups have produced reports that describe trends in U.S. research and innovation and set forth policy priorities (CED, 1998; Council on Competitiveness and Massachusetts Institute of Technology, 1998; House Committee on Science, 1998; NRC, 1999, forthcoming). All of these efforts recognize that science and engineering progress are central to achieving key national goals such as raising living standards, creating good jobs, ensuring national security, strengthening education, improving public health, and protecting the environment. They point out that U.S. science and engineering are vibrant today in large part because of strong support from public and private funders over many years.

There is also a consensus that the context for U.S. science and technology policies has changed fundamentally, and that the framework that brought success in the past needs to be rethought for the future. With some variation in emphasis, these recent reports cite major shifts such as the end of the Cold War, intensified global economic competition, and growing pressure for accountability and focus on the part of public and private research funders. Despite U.S. economic resurgence, real incomes for most Americans have only recently begun to rise again after two decades of stagnation. The United States also faces serious challenges with significant science and technology components in public health, education, national security, and the environment.

The U.S. research and innovation complex, comprising researchers and research institutions, funding agencies, educators, entrepreneurs, investors, and companies, is being pressed to adjust and reinvent itself. It is clear to COSEPUP that the United States needs to remain at the leading edge across all major fields of science and engineering research *and* to capitalize on this leadership to produce national benefits. Furthermore, the science and engineering community, along with the nation at large, must strive for continual improvement in the policies, institutions, and strategies that contribute to superior research and effective capitalization.

Several examples illustrate the challenges we face.

In the past few years the Internet has emerged as a major technological infrastructure in the global economy and a source of new wealth and jobs in the United States. This infrastructure is the result of U.S. public and private investments in research and related activities over many years. Yet some experts believe that long-term research activities in the public and private sectors are being shortchanged in the rush to pursue promising near-term product opportunities.[1] How can we

[1] This issue is discussed in more detail in Chapter 3. See also President's Information Technology Advisory Committee, 1998.

ensure that our national science and technology investment portfolio adequately supports the long-term work necessary to produce tomorrow's transforming innovations?

Also, the environment for financing science- and technology-based start-up companies is currently quite favorable because of low interest rates and strong U.S. equity markets. This mechanism for capitalizing on research has been a particular area of strength for the United States, and has produced numerous innovative companies, entire new industries, good jobs, and tax revenue. Yet the financing environment for start-ups has exhibited wide cyclical swings in the past, and we cannot assume that risk capital for new ventures will always be readily available. Further, some important areas where science and technology might be better applied to meet national needs, such as education, may not be attractive to venture capitalists and "angel" investors. How do we ensure that the United States maintains and expands its strengths in science- and technology-based entrepreneurial activity, while developing new pathways for capitalization?

As yet another example, the United States is on the leading edge of revolutionary progress in the life sciences. This work has the promise to significantly lengthen and improve our lives, as well as to create tremendous wealth. There is a growing, unmet demand for talented people who combine the skills needed for advanced life sciences research with knowledge of computers and an engineering perspective. Yet many students now receiving Ph.D. degrees in the life sciences lack this wider skill set and face difficult early career prospects (NRC, 1998). How can we balance the activities of research and education so that students receive the cutting-edge interdisciplinary skills demanded by industry and at the same time maintain a strong human resource base for academic life sciences research?

Finally, research partnerships and collaborations between academia, industry, and government have proliferated over the past 15 years. These often contribute to more rapid and effective capitalization and have produced a number of success stories such as those in semiconductors and data storage. However, sectoral differences in time horizons, goals, approaches to intellectual property, and other concerns can sometimes prevent smooth collaboration that leads to mutual benefits. Some types of partnerships, particularly those in which government provides funding to particular companies, remain controversial. And it is clear that the leverage provided by partnerships cannot serve as a substitute for long-term government support in some areas of research. How can we build on our growing experience base to structure stronger, more productive partnerships between sectors?

Given this context, it is evident that capitalizing on investments in science and technology is a vital national imperative and that the United States faces long-term challenges in maintaining and enhancing our ability to capitalize.

PURPOSE OF THE STUDY

How does COSEPUP expect this study to contribute to the ongoing national debate?

In recent, ongoing projects, COSEPUP has examined many aspects of the changing science and technology policy environment, including the basic framework for federal science and technology policy, the development of human resources, the federal investment portfolio, international benchmarking of U.S. research in several important fields, and accountability in federal research investments (COSEPUP, 1993, 1995, 1996, 1997a,b, 1998, 1999a,b,c). To reshape our national approaches to science and engineering education, research funding, and other issues, it is necessary to understand how these approaches might affect the nation's ability to capitalize on science and technology to produce national benefits.

This study addresses three basic questions:

- How well is the United States capitalizing on its investments in science and technology?
- What factors are responsible for its successes?
- What can be done to maintain and improve this performance in the future?

Innovation, technology transfer, and the commercialization of research have been the subjects of numerous studies. This project takes a somewhat different approach in assessing how well the United States harvests returns on investments in science and technology, in the form of better economic performance (including creation of jobs and tax revenue), stronger education, improved public health, and other national benefits. The report draws on an examination of specific examples of research and application, as well as crosscutting issues such as strengthening human capital and financing of science- and technology-based ventures. The findings and recommendations identify key areas for scientists and engineers, policy makers, and others to focus their efforts in the future.

In the course of this study, COSEPUP gained a renewed appreciation for the importance and complexity of capitalization, a better understanding of the necessary elements, and new insights into U.S. strengths and weaknesses. The report is intended to communicate these perspectives to the broader communities concerned with science, engineering, and policy issues.

SUMMARY OF FINDINGS

A number of findings and action points echo those of other recent reports. COSEPUP is encouraged by this confluence of ideas and hopes that this effort may contribute to a growing national consensus on key issues of science and technology policy. Although several of the tasks that COSEPUP identifies will be familiar to those regularly engaged in these issues, they remain critically important for the ability of the United States to capitalize over the long term.

Finding 1: Capitalization on science and technology is a major national strength, although there is much room for improvement. Capitalization appears to be quite healthy in the United States today, delivering significant benefits to the nation. Nonetheless, COSEPUP believes that there are many areas where U.S. approaches can be improved. As outlined in various parts of the report, the United States has significant weaknesses, and complacency could lead to a decline in its strengths.

This finding contrasts with the situation a few years ago, when several U.S. industries faced serious challenges in global markets (Dertouzos et al., 1989). Foreign-based companies had used superior product development and manufacturing quality to surge ahead in high-technology industries pioneered in the United States. Some observers, pointing to continued U.S. strength in basic research, concluded that the United States was losing the ability to capitalize on its research investments, and allowing foreign countries to reap the lion's share of benefits (Prestowitz, 1988).

As this is written, the situation looks quite different because of two important shifts. First, many established U.S. companies and industries have improved their performance in product development, manufacturing, and marketing.[2] Second, a wave of new industries and companies has arisen in the United States, many of them with clear and direct links to public and private research efforts initiated several decades ago (such as the Internet and life sciences examples cited above). Both of these trends have benefited from, and contributed to, a favorable macroeconomic environment.

Finding 2: The key elements contributing to effective capitalization are

- *strong, stable funding for a portfolio of research investments that is diverse in terms of funders, performers, time horizons, and motivations;*
- a *favorable environment for capitalizing, characterized by a strong incentive structure for investors, competition in the market, and free movement of ideas and people between institutions;*
- *a skilled, flexible science and engineering human resource base that allows the United States to maintain research at the cutting edge and capitalize effectively;*
- *mechanisms for research and capitalization that support cooperation between academia, industry, and government.*

SUMMARY OF RECOMMENDATIONS

Recommendation 1: To ensure a strong, stable, diverse portfolio of S&T investments, incorporate an explicit and continuing concern for capitalizing into the allocation of federal research funding. Despite concerns over whether the United States should continue to fund a large share of the world's openly available research, it is clear to the committee that the ability to perform research at the cutting edge across all major fields does deliver significant national benefits. Researchers, policy makers, and businesses must understand that a strong, diverse portfolio of research investments generates the most powerful "fuel" for innovation and sharpens the ability to make use of important advances wherever they occur. Policy makers should strive to maintain all stages of investigation: fundamental research, applied research, and fundamental technology development.

[2] This improvement is covered in Chapter 2 and in much greater detail in STEP (1999).

Based on conditions observed in several of the fields examined during the course of the study and other recent COSEPUP work, the committee believes that a current, pressing task for the federal government is to ensure sufficient funding for long-term science and engineering research, including research infrastructure.

■ In the current climate of general pressure toward shorter time horizons in research, the federal government should pay close attention to its role as "funder of last resort" of long-term science and engineering research.

■ Evaluations of research funding performance should recognize the importance of capitalization and seek to identify the long-term contributions of research to meeting national goals, both within specific fields and across the U.S. science and engineering enterprise.

Recommendation 2: Maintain a favorable economic and regulatory environment for capitalizing on research. At present the major features of a supportive environment are in place and should be maintained. COSEPUP found that capitalizing is a complex process with multiple feedback loops, but that public policies play an important role in supporting or hindering its effectiveness. The public policies and private strategies needed to maintain and enhance capitalization in the United States should be adapted to evolving world conditions.

■ Federal and state governments should ensure that individuals and institutions continue to have strong incentives to capitalize on research.

■ Universities should continue to review and update policies that affect capitalizing on research in order to sustain and expand their contribution.

Recommendation 3: Regard the education and training of scientists and engineers as an essential ingredient for capitalizing on research. Universities are responsible for preparing scientists and engineers to play crucial roles, both in generating new knowledge and in capitalizing on that knowledge. Students must be prepared for capitalizing roles as well as they are prepared for research roles. Federal agencies, which finance a large share of advanced science and engineering education, should seek to understand how various funding mechanisms affect human resource development. Industry should also take a more active role in preparing students for nonacademic careers through mentoring, communicating their employment needs, and arranging internships.

■ Universities, cooperating with science and engineering societies, government, and industry, should develop mechanisms to recognize signals of manpower shortages or gluts, and communicate this information to students.

■ Agencies that support advanced research and education should enhance diversity in funding mechanisms and develop ways to measure the effects of alternative approaches.

■ Industry, universities, and government must recognize the importance of lifelong learning for the nation's science and engineering human resources.

Recommendation 4: Build stronger partnerships between academia, industry, and government. Universities, industry, and government are still learning which approaches lead to successful partnerships. They should build on the most successful intersectoral partnerships to develop precompetitive technologies and speed the diffusion of new knowledge and technologies. At the same time, partnerships should not be viewed as a panacea, and leveraging of industry funding should not be expected to substitute for strong federal investments.

- Governments, industries, and universities should continue to experiment with partnerships and consortia.
- State and federal governments should help to arrange new partnerships and arbitrate issues of rights and ownership.

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Chapter 1

INTRODUCTION

This report, by the Committee on Science, Engineering, and Public Policy (COSEPUP) of the National Academy of Sciences (NAS), the National Academy of Engineering (NAE) and the Institute of Medicine (IOM), was motivated by a report on U.S. science and technology goals (COSEPUP, 1993). That document (the Goals report) recommended two related objectives: "(1) that the United States should be among the leaders in all major fields of science, and (2) that the United States should seek to maintain preeminence in selected fields of national importance." These recommendations reflect the view that scientific and technological advances are fundamental to improving the nation's economy, public health, education, environment, and quality of life.

The Goals report, like other recent reports, refers to the process by which the results of research may be transformed into new ideas, processes, and techniques that benefit the nation. This complex process, which includes technology transfer, innovation, commercialization, application, and other components, is described in the present report as "capitalizing on investments in science and technology." COSEPUP's goals are to call attention to a process of significant complexity and great importance to the nation, to demonstrate the importance of a supportive capitalizing environment, and to suggest ways in which capitalizing might be strengthened.

The members of COSEPUP concluded that in recent years the United States generally has been effective in capitalizing on research, whether it is performed in this country or abroad. At the same time, COSEPUP feels that the U.S. research, entrepreneurial, and policy establishments need to understand the capitalization process better if the nation is to maintain and extend this effectiveness in the future.

This report seeks to contribute to the ongoing science and technology policy debate by raising three basic questions: What are the principal features of the capitalizing process? How are they likely to be affected by the changes sweeping across science, technology, and the economy? In the face of these changes, how can we maintain and extend the effectiveness of capitalization?

This study, which was planned by a working group organized under COSEPUP, has involved two main thrusts. The first is the use of workshop discussions and a survey of relevant literature (see Appendix A for examples of capitalization) to examine particular fields of research and their applications. The working group discovered that its questions were best addressed through the examination of specific examples in subfields that are fairly well defined, such as speech recognition and monoclonal antibodies, rather than overviews of broader fields, such as computer science and biology. Although the number of fields examined is not large, the working group tried to choose areas that would illustrate a range of scientific, engineering, and capitalization issues.

The second thrust of the study consisted of additional workshops, commissioned papers, and other activities that address crosscutting issues. These issues include the role of private finance, educational and human resource issues, and the economic environment for investments in research and commercialization. Throughout, the working group has given particular attention to human resources, expanding on the theme of another COSEPUP (1995) study.

On the basis of these two thrusts, COSEPUP developed an understanding of the capitalization process as the transformation of research investments into national benefits. In Chapter 2, the working group discusses the workings of the capitalization process and the elements that favor capitalization, such as an environment conducive to financing new technology-based businesses and a system of education and training that produces graduates who are not only skilled but also flexible and adaptable. Chapter 3 examines the changes in the education, legislative, and economic climates that bring new challenges to the capitalization process. Chapter 4 discusses the the study findings and the important tasks facing the United States as it seeks to maintain and enhance its ability to capitalize on research leadership. Chapter 5 presents the working group's recommendations.

A considerable part of the working group's focus has been on the economic and commercial benefits of capitalizing on research. This is partly because commercial benefits often can be identified and measured, and because the economic returns to capitalizing on research are widespread and have an important effect on everyday life. Still, capitalizing on research is understood to lead to other important benefits, and several aspects of the project illustrate how research leads to national advantages in other areas, such as education, public health, environmental protection, and national security.

Discussions about capitalization are fueled by new conditions, especially the globalization of commerce, the emergence of advanced technological capability throughout the world, and experiments to transform the mission of federal research and development agencies in the wake of the Cold War. Policy choices that will be made in the near future have the potential to shape science policy for years to come. It is time for scientists and engineers to contribute their expertise, to demonstrate how their work delivers benefits to the nation, and to join in the process of defining and prioritizing national goals.

The study was supported by the Alfred P. Sloan Foundation, the National Institutes of Health, and the National Research Council.

Chapter 2

THE CAPITALIZING PROCESS

The United States' leadership in research across the spectrum of science and engineering is well known. Less well known to the general public is its effectiveness in transforming the results of research into concrete national benefits. This transforming process is called capitalization: *Utilizing the results of research to advance national goals, such as maintaining a high standard of living, creating high-paying jobs, improving education, protecting the environment, enhancing personal and public health, ensuring national security, and deepening human understanding.*

CAPITALIZING ON RESEARCH: AN OVERVIEW

Innovation, technology transfer, and the commercialization of research have long been a focus of academic study and policy debate. In undertaking this study, the working group sought to better understand how science and technology investments by government and industry are transformed into national benefits.

The long-term role of science and technology in raising living standards has become more apparent in recent years, as the growth of science- and technology-based companies and industries has lifted U.S. economic performance. A striking example is the continuing explosion of innovation and business opportunities surrounding the Internet.

The groundwork for the Internet was laid by basic technology research in university and other laboratories, and was funded largely by the federal government, especially the Department of Defense (DoD) through the Defense Advanced Research Projects Agency (DARPA) (see Box 2-1). Starting in the late 1960s, DARPA helped to create the ARPANET so that universities could share expensive research computers.[1] During the 1970s a growing number of researchers used this network as a communications medium within the science and engineering community, and the National Science Foundation (NSF) became its primary sponsor. Software was developed to use the new "Internet": Physicists in Geneva invented the World Wide Web to share data via hypertext, and graduate students at a federally funded computer center in Illinois added a browser called Mosaic. Finally, private firms leapt into the field, offering to help isolated desktop

[1]Hafner and Lyon (1996). Research during the early 1960s by Paul Baran and others developing the concept of packet switching, a key enabling technology for the Internet, was aimed at making communications secure in case of a nuclear attack.

BOX 2-1
An Internet Chronology

Early 1960s: Research begun on packet switching, a key enabling technology for the Internet.

1969: Defense Department commissions ARPANET to promote networking research, Bolt, Beranek and Newman wins design contract.

1974: Robert Kahn and Vinton Cerf publish paper specifying TCP/IP protocol for data networks.

1981: NSF provides seed money for CSNET (Computer Science NETwork) to connect U.S. computer science departments.

1982: Defense Department establishes TCP/IP protocol as standard.

1984: Number of hosts (computers) connected to Internet breaks 1,000.

1986: NSFNET and five NSF-funded supercomputer centers created. NSFNET backbone operating at 56 kilobits/second.

1989: Number of hosts passes 100,000.

1991: NSF lifts restrictions on commercial use of the Internet. World Wide Web software released for public use by CERN.

1993: Mosaic browser developed for public use at NSF-funded supercomputer center at University of Illinois.

1995: U.S. Internet traffic carried by commercial service providers.

1996: Number of Internet hosts reaches 12.8 million.

Source: SRI International, *The Role of NSF's Support of Engineering in Enabling Technological Innovation*, 1997.

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computers "get connected," and the Internet exploded into homes and businesses around the world.

Over three decades, the Internet has moved from a government-sponsored to a market-driven network, with much of the development taking place outside the realm of science. To illustrate the power of capitalization, consider that DARPA's original 1969 contract with Bolt, Beranek, and Newman, to set up the first nodes on the ARPANET, was for only $1 million. As this report was being prepared, the combined market value of just five networking firms, none of which existed before 1980, approached $150 billion.[2] One survey firm estimates that there were

[2]The five firms are America Online, Amazon.com, Cisco Systems, Netscape, and Yahoo!, whose market value on September 29, 1998, was approximately $148 billion. For background on the development of the Internet and future issues, see CSTB (1994).

102 million Internet users worldwide as of January 1998, and that the number of users has been almost doubling every year for the past decade (Matrix Information and Directory Services, 1998).

The economic benefits of capitalization are vital, and obvious. For example, most econometric studies of research and development (R&D) investments have found that the private returns on these investments exceed 20 percent and the social returns exceed 50 percent.[3]

In the case of the Global Positioning System (GPS), research investments made over a long period of time in a number of different fields resulted in a capability that first enhanced U.S. national security, and is now producing an explosion of civilian uses (*Beyond Discovery,* 1996b). In the case of monoclonal antibodies, research breakthroughs during the 1970s led directly to the development of tests that enable the United States and other countries to eliminate the risk of transmitting AIDS through blood transfusions (see Appendix A). This contribution to public health is now being amplified by significant economic returns.

The complexity of capitalization

As Richard Nelson (1998) notes, technological advance involves uncertainty in a fundamental way. The process is full of surprises, and it generally is not possible to predict the outcomes of research programs. For years, experts have been trying to develop useful models and definitions to categorize various part of the research and innovation process. R&D statistics and policy discussion often reflect assumptions of a linear model, by which innovation proceeds from fundamental discovery to applied research, and then to development and marketing. However, there is widespread recognition that this model is not adequate to describe most real-world innovations.

The late Donald Stokes (1997) explored this question in depth, dividing research activities into four "quadrants" according to whether they are performed through "considerations of use" or a "quest for fundamental understanding." Stokes succeeds in showing that the progress of research is as complex as the motivations and abilities of the people who perform it. For example, sometimes major advances in fundamental knowledge are made by those working on practical, short-term problems.

In developing the idea of *capitalization* as a process of realizing returns on investments in research, the working group has adopted some conventional terms, such as basic (or fundamental) and applied research.[4] Yet the examination of specific examples reveals the problematic nature of such categories. Even the simplest research project involves complex flows of information between applications, under-

[3]For a tabulation of various studies, see Council of Economic Advisors (1995). As described below, our understanding of the mechanisms that link science and technology investments and economic growth is incomplete.

[4]For a discussion of the similarities and differences between fundamental research in science and engineering, see NAE (1995a).

lying principles, and work already done by others. The capitalization process in its entirety is a field of complex interactions and feedback loops between individuals, institutions, and the environment in which it occurs.

Some radical research breakthroughs lead to quick capitalization by existing companies and industries; a number of significant advances in catalysis were capitalized upon quickly. Other radical innovations prompt new companies to emerge; this was the case with monoclonal antibodies. The life-sciences and health-oriented research communities have produced a number of breakthroughs leading quickly and directly to capitalization. In other cases, capitalization results from incremental improvements in the design or manufacturing process of proven products. Although the semiconductor industry has benefited from several major breakthroughs, much of the work responsible for the development of successively more powerful integrated circuits over the past 30 years has been incremental. The improvement of chemical processes through advances in catalysis has benefited from both radical and incremental advances (see Appendix A).

Other successful examples of capitalization examined by the working group have depended upon accumulated advances in several different fields. In the case of speech recognition, advances in the modeling of human speech and software design, combined with the vastly improved performance of computers, enabled the first commercial applications during the 1980s. This occurred after decades of government and industry research.

In light of the complexity and unpredictability of the capitalization process, the working group decided not to attempt a particular model of capitalization, although it has made use of definitions and categories developed by others. The working group also has confirmed that capitalization, despite its complexity, is amenable to increased understanding and improvement through effective public policies and private strategies. Four elements of the process are discussed in this report: (1) research and research investments, (2) the environment for capitalizing, (3) human resources, and (4) partnerships and other cooperation between sectors.

RESEARCH AND RESEARCH INVESTMENTS

Investments in research, development, and commercialization create fuel for the engine of capitalization. Because investments in research must compete with other national priorities, research funding is a topic of perennial debate among policy makers. The federal government provides over one-third of total research funding (the rest comes primarily from industry), and so, the debate is a public one, flavored by the pressures and demands of the political process.[5] What kind of research should be funded? Why should it be funded by the government? How do we know it will bring the results we want?

[5] For comprehensive statistics on R&D funding and other aspects of the science and engineering enterprise, see National Science Board, (1998).

Research never fits easily into discrete categories. Much basic science and engineering research is performed with specific uses in mind, especially uses imagined by the funder; both applied research and technology development often provide new questions and tools for basic research and advance the frontiers of fundamental understanding. Many of the most interesting and useful science and engineering questions lie in the gray zone between the quest for fundamental knowledge and the development of specific products.

Just as it is not easy to classify research activities, it is not easy to decide what kinds of research deserve support. Many products that today serve the public good also are sold commercially and grew out of a complex ferment of investigation. For example, early in its development, research into magnetic resonance imaging (MRI) was led by academic scientists based in the United Kingdom.[6] Some of them were physicists interested in imaging phenomena, whereas others were medical researchers interested in clinical diagnostics. The British government supported both kinds of research, which have resulted in one of the most important recent advances in medical technology. MRI produces a two- or three-dimensional image of internal body structures that previously required invasive surgery or arthroscopic procedures. Once the potential uses of MRI became clear, commercial firms in several countries took over problem-solving and development.

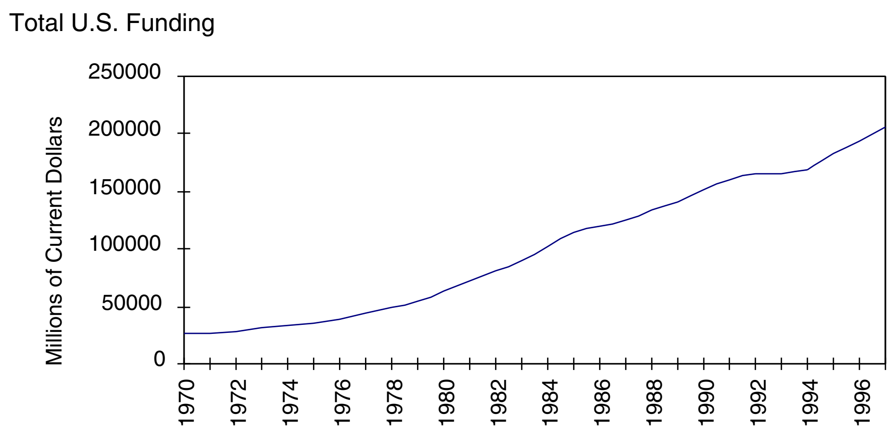
The examples examined by the panel show that the federal government and industry have vital and complementary roles in funding research. Long-term and stable federal support has maintained U.S. capabilities to perform research at the frontiers of all major fields, and has been critical to capitalization. A diverse funding portfolio is characterized by multiple funders supporting research in industry, universities, and government laboratories, and by competition between researchers and institutions. Such a portfolio is vital to sustain the search for new knowledge, the growth in our stock of scientific and engineering human capital, and the necessary infrastructure.

The importance of public investments

It generally is understood that public investment in research is critically important to achieving societal goals. The federal government funds a large portion of U.S. basic research, and the size and allocation of funding are perennial topics of debate, featuring considerable swings and variations. Figures 2-1 through 2-4 show the longer-term trends in public and private support.

The federal component of research funding, because of its size and stability, is essential for several reasons: it can support complex laboratory facilities unavailable anywhere else, it can sustain long-term research that leads to technologies unimagined when the research was initiated, it educates the nation's scientists and engineers, it helps universities to maintain free access to knowledge, and it can pay for infrastructure and instrumentation technologies essential to research.

[6]Stanford Research Institute (1997). The development of MRI relied on basic research on nuclear magnetic resonance going back many years before that.



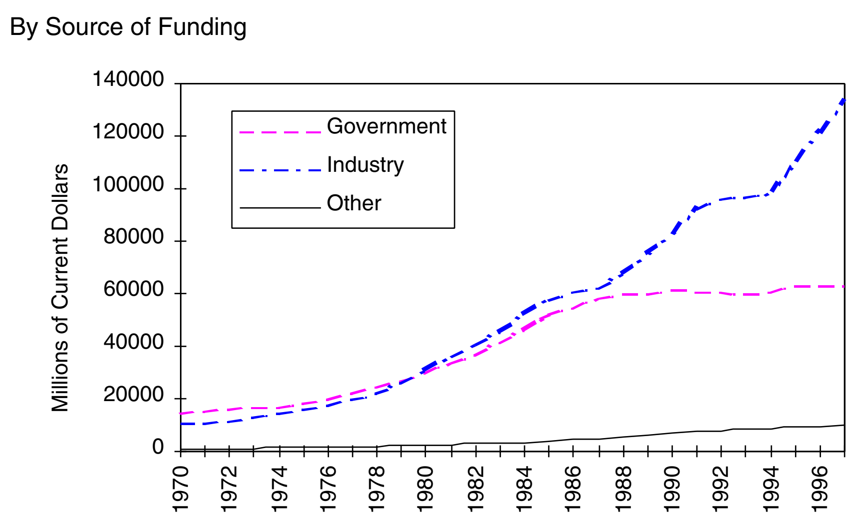


FIGURE 2-1 U.S. Research and Development Expenditures (Current Dollars).
Note: Industry figures before and after 1991 may not be directly comparable due to changes in the survey. Source: National Science Foundation, Science and Engineering Indicators, 1998. Appendix Table 4-5.

For example, federal government support played an integral role in the development of the GPS.[7] GPS satellites continually send out radio signals giving their exact position and time. Military and civilian users with GPS receivers can pinpoint their position on Earth's surface with a high degree of accuracy using these signals. The development and deployment of GPS required $12 billion in DoD funding and years of effort on the part of DoD and its contractors. In addition to

[7]See *Beyond Discovery* (1996a). This write-up focuses on the role of atomic clocks. For a description that highlights the role of a key contractor, The Aerospace Corporation, see (www.aero.org/publications/gps/).

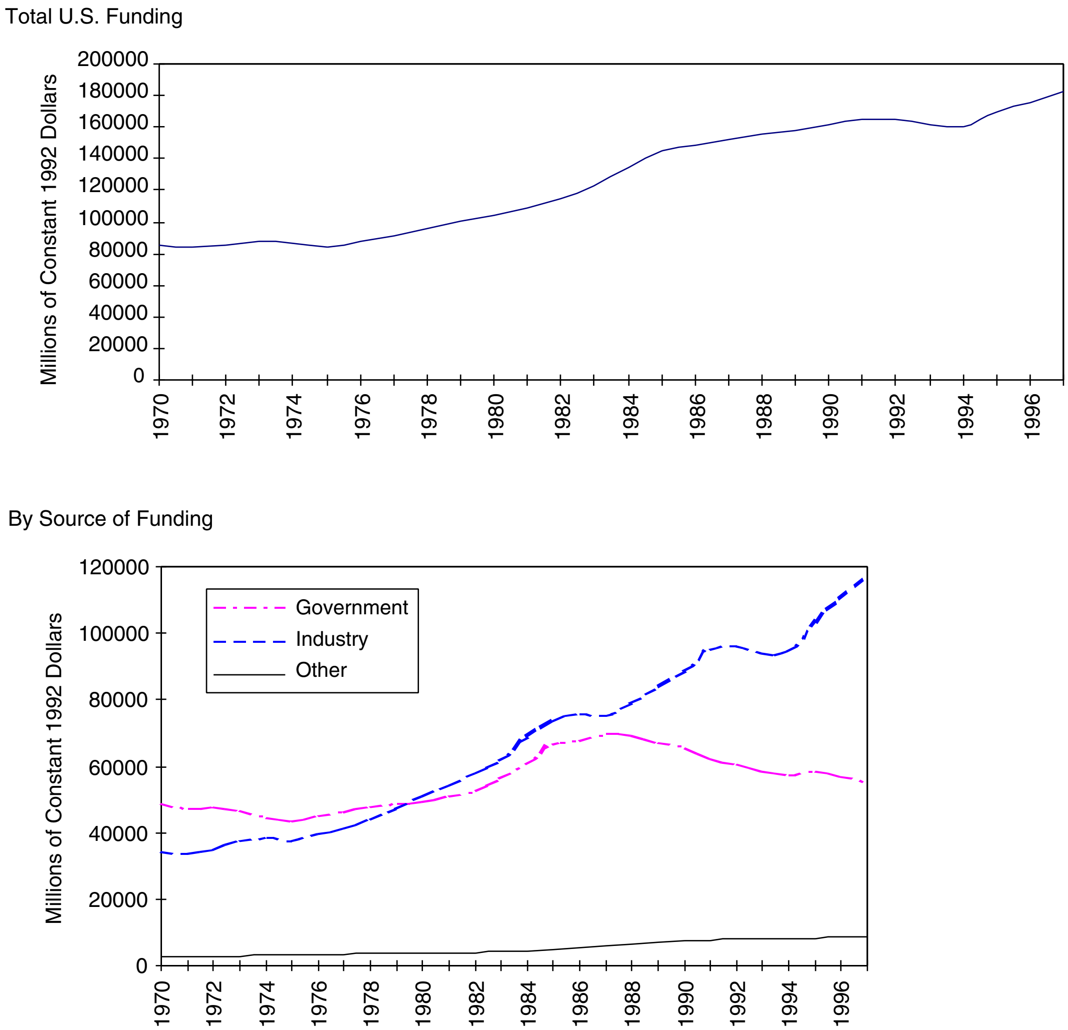


FIGURE 2-2 U.S. Research and Development Expenditures (Constant Dollars). Note: Industry figures before and after 1991 may not be directly comparable due to changes in the survey. Source: National Science Foundation, Science and Engineering Indicators, 1998. Appendix Table 4-6.

R&D efforts directly related to the system, GPS draws on a range of science and engineering advances generated in large part through federal support, including satellite launch and control technologies, microwave communication, and micro-electronics. Atomic clocks, which are carried on every GPS satellite, were enabled by fundamental insights in quantum physics prior to World War II, with some important development work during the 1950s supported by the National Bureau of Standards [now the National Institute of Standards and Technology (NIST)].

Originally developed and deployed as a tool for the U.S. military, GPS is increasingly important as an infrastructure for civilian travel and navigation. To-

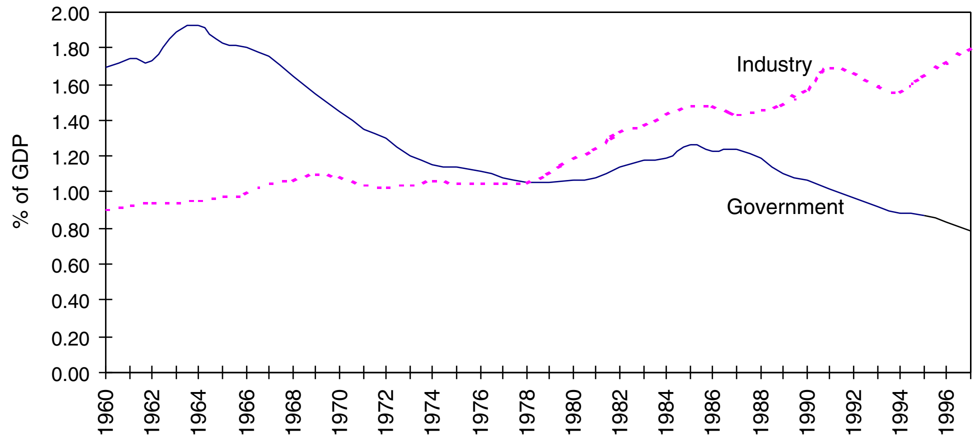


FIGURE 2-3 R&D Spending as a Percentage of GDP.

Note: Industry figures before and after 1991 may not be directly comparable due to changes in the survey. Source: National Science Foundation, http://www.nsf.gov/sbe/srs/natpat97/start.htm, Table 7.

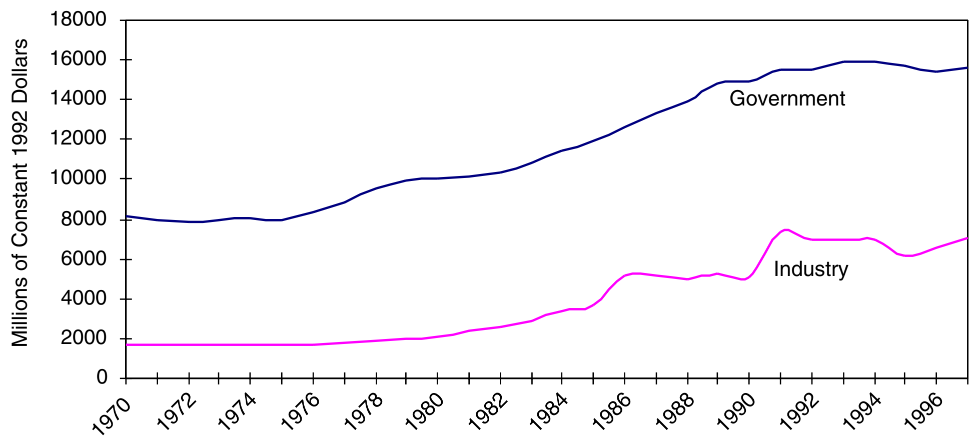


FIGURE 2-4 Basic Research Spending by Source.

Note: Industry figures before and after 1991 may not be directly comparable due to changes in the survey. Source: National Science Foundation, Science and Engineering Indicators, 1998. Appendix Table 4-10.

day, sailboats, crop dusters, automobiles, and backpackers can all carry GPS receivers. Combined with computerized "yellow pages," the GPS will allow travelers everywhere to find a local restaurant, gas station, or hospital in an instant. The worldwide market for products and services enabled by GPS is expected to surpass $30 billion in the next decade. GPS illustrates that capitalization on research often occurs in complex, unpredictable, and nonlinear ways. The case also shows that important science and engineering applications often rely on research advances in a number of fields and supported by a variety of funders.

Another field that depends on publicly funded research is human gene testing, where a half-century of basic biological research has led to discovery of over 50 disease genes. Today, this knowledge gives doctors a better chance of detecting disorders early and developing treatments. Prenatal genetic testing for fatal or debilitating conditions, such as Tay-Sachs disease, is reducing their incidence in the general population (*Beyond Discovery*, 1996b).

In terms of economic value and many Americans' work habits, federal support of computer science and telecommunications has been of utmost importance. A survey by the Computer Science and Telecommunications Board of the National Research Council found that federally funded university research underlies many commercially important technologies that evolved between 1965 and 1994, including time-sharing, graphics, networking, workstations, windows, RISC, VLSI design, and parallel computing. It also presented a model that graphically demonstrates how complex and nonlinear is the innovation process [CTSB (1997); see also CTSB (1998)].

The importance of private investments

In several of the examples considered by the working group, the ultimate success in capitalization has depended on industrial and other private investments. The invention of the transistor at AT&T Bell Laboratories over 50 years ago and its subsequent application is a well-known example. Similarly, in catalysis, large chemical and petrochemical companies in the United States and Europe produced many of the major advances in their own labs or funded the work at universities (see Appendix A).

The importance of government research investments in developing the computer industry was discussed in the preceding section; industry investments have been just as critical. For example, the Xerox Palo Alto Research Center (PARC), founded in 1970, has played a key role in developing laser printers, graphical user interfaces, object-oriented programming languages, and Ethernet local area networks.[8] Although Xerox itself did not capitalize on many of PARC's advances, particularly those underlying the personal computer, they were commercialized by Apple, IBM, and a number of start-up companies, including Adobe Systems, that were led by PARC alumni. In 1988, Xerox Technology Ventures was established to create entrepreneurial companies, which are owned jointly by Xerox and by employees, to capitalize on promising in-house technologies.[9]

Today, companies such as SmithKline Beecham and Merck are investing in long-term research in bioinformatics, a promising area combining tools and insights from the life sciences and computer science (Marshal, 1996).

[8]Xerox PARC website: http://www.parc.xerox.com/AboutPARC.html

[9]*Christian Science Monitor* (1994, quoting Charles Hart, Semaphore Communications Corporation).

The importance of financing for new science- and technology-based companies, a particular type of private investment, is examined in more detail in the next section.

The value of a diverse research portfolio

The diversity of the U.S. research effort and its funding are sources of strength. It is a system that thrives on pluralism, with many sources of support, many performers, and a maze of linkages among funders, performers, and users of research. A diverse research culture also contributes to competition among researchers and helps to avoid overspecialization or neglect of potentially important fields.

The diversity and pluralism of the U.S. science and engineering enterprise is illustrated by the pattern of federal government support. In the United States, agencies pursuing defense, health, space exploration, and energy missions provide the bulk of federal R&D support, with the NSF also playing an important role. This contrasts with some other industrialized countries, where government agencies responsible for science and technology, economic development and education play the major role in supporting research, particularly in nondefense areas.[10]

In several fields examined by the working group, U.S. ability to capitalize on research has been enhanced by its ability to work at the forefront of all major science and engineering fields. In the field of monoclonal antibodies, excellence in immunology research allowed U.S. researchers and start-up companies to capitalize on research advances made abroad. Excellence in computer science and the life sciences is allowing U.S. scientists to capitalize quickly in the area of bioinformatics.

A truism holds that once the results of research are published, that knowledge becomes a public good, equally available to all. Availability, however, is no guarantee of the ability to utilize public information advantageously. To capitalize on a research result, one needs the technical ability to understand it and capture its benefits, the availability of complementary research inputs, the economic ability to finance development and commercialization, and the regulatory protection of ownership. When scientists working at IBM's laboratory in Switzerland found that superconductivity could occur at temperatures of 40 K, U.S.-based scientists were quickly able to demonstrate superconductivity at temperatures above that of liquid nitrogen, but only because they were already conducting research on superconductivity. In other words, the human capital necessary for capitalization is a "joint product" with performance of basic research. This has been the most productive way to produce this type of human capital.

The importance of research diversity is illustrated in a four-year study by Stanford Research Institute to analyze the driving forces behind crucial technologies. The first three technologies studied by SRI appear to have developed by

[10]One example is Japan, where in fiscal 1996 the Ministry of Education, Science, Sports, and Culture, the Science and Technology Agency, and the Ministry of International Trade and Industry accounted for over 80 percent of government science and technology spending. See Science and Technology Agency (1996).

quite different routes. For reaction injection molding (RIM), the primary driving force appeared to be demand from the auto industry for RIM products, spurred by government safety regulations. Industry conducted much of the necessary research itself, and both industry and government supported critical academic research by University of Minnesota chemical engineer Christopher Macosko. In the case of MRI, crucial forces were basic science research on nuclear magnetic spectroscopy and educational support for graduate students. In the case of the Internet, the key forces were sustained government funding, flexible university research, and visionary leadership (Stanford Research Institute, 1997). Each of these programs allowed maximum flexibility on the part of researchers; all culminated in outcomes whose dimensions had not been imagined beforehand.

A number of the examples considered by the working group illustrate how long-term investments in research and advanced education have allowed the United States to capitalize on them and to pioneer new fields. In speech recognition, for example, industry and government both invested for a long period of time—a period of "research gestation"—before the field gained momentum.

In all of these cases, science and engineering research and technology development were intertwined. Harvey Brooks has suggested that "pure technology" is as appropriate for public investment as "pure science." He cites the example of radioisotopes and stable-isotope tracers; studies were supported by the Atomic Energy Commission for many years before the medical and biological communities learned how to use them. Today, they are vital tools for diagnosing and treating disease and for basic biological research. Only by creating a strong research infrastructure and educated human talent can the nation fully capitalize on research.

HUMAN RESOURCES AND CAPITALIZATION

Producing and harvesting the fruits of research must be done by talented scientists and engineers who can create and transform new knowledge into uses that are aligned with national goals. The working group found that the human resource aspects of capitalization are much more important than is generally realized. To a very large extent, the most important long-term outcome of federal investments in research is to educate the next generation of scientists and engineers and to support the continuing education of those already in the workforce.[11] Employers who understand the lifelong value of learning generally are willing to support on-the-job training, night courses, and even full-time courses leading to advanced degrees.[12]

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[11]In 1995, about 20 percent of full-time science and engineering graduate students reported that their primary source of support was the federal government, almost 47 percent reported that they were primarily supported by nonfederal funding, and 33 percent reported that they were primarily self supporting. This survey underestimates total federal support because reporting on federal sources includes only direct support to students and support to research assistants financed through the direct costs of federal research grants. See National Science Board (1998).

[12]Motorola is one U.S. company that maintains an extensive in-house training and education capability, Motorola University (www.mu.motorola.com).

Effective capitalization on science and technology requires a broad range of skills and talents. Outstanding researchers contribute by creating new knowledge. Entrepreneurs and corporate managers see new business opportunities and put research to work in order to pursue them. Policy makers and program managers in government are charged with linking research with national needs. Investors provide risk capital for new science- and technology-based enterprises.

Specialized science and engineering training is not necessary for all of these roles. Still, the contribution of scientists and engineers to capitalization is striking, in research and nonresearch roles. For example, visionary program management by DARPA and NSF scientists and engineers made key contributions to the launch and subsequent growth of the Internet (Hafner and Lyon, 1996). Life scientists who make discoveries with significant potential for application often play a role in capitalization as the founders or scientific advisers of new companies (Stephan and Everhart, 1998). Partners in venture capital firms often have science or engineering training as well as experience in business.

U.S. scientific and engineering human resources owe much of their strength to the practice of coupling advanced education with cutting-edge research, much of which is funded by the federal government.[13] The realism, depth, and intellectual challenge of formulating and solving research problems constitute powerful means of preparing students for productive careers. The effectiveness of this system draws students from around the world, many of whom remain to teach, perform research, and contribute to capitalization in this country.

Most students gain their early research experiences through teachers and advisors. Typically, the advisor's research is supported by a public grant that includes provision to hire graduate students as research assistants. The research assistantship supports students financially and involves them in research. The advantage of the research assistantship is the intense involvement of the student in an authentic research experience under a faculty mentor.

Research assistantships have become the predominant form of federal support for graduate education in science and engineering over the past several decades (COSEPUP, 1995). Over the same period, direct support to students through fellowships and training grants has declined in importance. In a previous report, COSEPUP (1995) recommended efforts to diversify the mechanisms for student support.

There are good reasons for maintaining diverse support mechanisms for advanced science and engineering education. Although research assistantships give students valuable first-hand experience in research, exclusive reliance on this form of support by individual students can carry disadvantages. For example, the pressure on faculty to produce research results may be transferred to students. Students may become so involved in a specific research project that little time is left to gain a broad appreciation of their field or gain skills and experience needed for nonacademic career paths.

[13]Because they help to create and sustain excitement and interest in particular fields, federal research funding decisions carry importance beyond the actual dollar amounts.

Likewise, science and engineering education can be enhanced by the introduction of other skills and experiences relevant to the capitalizing process. Diversified support in the form of traineeships and corporate internships can help students to gain these skills and experiences. For example, students may profit from exposure to nonacademic environments where they are likely to find employment, notably in industries and mission agencies. And they may benefit from learning skills that are useful in many positions, such as research planning, team building, management, product development, marketing, public policy, and business principles. Graduating students who possess such skills are powerful agents of technology transfer as they establish their own academic careers, join industry or the federal government, or start new companies.

Whereas the research environment is essential to graduate students, it is also important to undergraduate education. The undergraduate often is inspired by learning in an environment where new discoveries are occurring and where science and engineering are seen as vibrant, ever-changing professions. Many of the key roles in capitalization are played by those who receive undergraduate training in science or engineering, and then go into careers in business or other professions.

Scientists and engineers as entrepreneurs

The ability of scientists and engineers to move out of the laboratory to manage and even found their own businesses is a powerful feature of the U.S. capitalizing environment present in few other countries. In this way, scientists and engineers can be effective agents of technology transfer to address real-world problems, and add greatly to the entrepreneurial strength of the United States (Roberts, 1991).

One prominent example of a scientist-engineer-entrepreneur is Alejandro Zaffaroni. Zaffaroni was born in Uruguay, where he studied medicine. After receiving a doctorate in biochemistry from the University of Rochester, New York, he went to work for Syntex, then a small firm headquartered in Mexico City. Zaffaroni's work with Dr. Carl Djerassi became the basis of the Pill, or oral contraceptive, a product that transformed Syntex into a large pharmaceutical company.

Zaffaroni went on to found several other firms, including ALZA Corporation (a leader in drug delivery technology), DNAX Ltd. (manufacturing macromolecular products for medicine), Affymax (exploiting a technology that permits the parallel synthesis and screening of compounds for pharmacological activity), and Affymetrix (managing genetic information). As a scientist/entrepreneur, he continues to work in the fields of drug delivery and drug discovery. Firms founded by Zaffaroni have been fertile training grounds for other entrepreneurs.

Certain academic communities, where many entrepreneurs with science and engineering backgrounds are found, have a large impact on the transfer of ideas to the marketplace. The Bank of Boston has measured the economic contribution of companies founded by Massachusetts Institute of Technology (MIT) graduates and faculty and found that 4,000 MIT-related companies have annual world sales of $232 billion (BankBoston, 1997).

THE ROLE OF PARTNERSHIPS

Many fast-growing, emerging fields, such as telecommunications and biotechnology, are broad and multidisciplinary. Capitalizing on research in these areas may require expertise in several disciplines that span basic, applied, and developmental activities. One way to achieve this expertise is through partnerships between public, private, and educational institutions. The working group's examination of partnerships shows that they can be valuable, but cannot ensure effective capitalization by themselves. For example, industry-university partnerships cannot be expected to serve as a substitute for the federal government as funder of most basic research and the educational component of research.

Industry partnerships with universities

A valuable agent of capitalizing is the "permeable membrane" between universities and industry which allows a relatively free flow of people and ideas. Government often facilitates this flow in its role as a customer for research. There are two principal benefits of this flow:

1. Industry gains access to trained people, new ideas, and new processes;
2. Universities gain financial support for research and education, exciting real-world problems, intellectual feedback, consulting opportunities for faculty, and internships and employment possibilities for students.

Over the past several decades, U.S. industry has expanded its support for university research.[14] Much of this support takes the form of sponsored research, technology licensing, graduate fellowships, consortia, or faculty consulting, without being institutionalized in special programs or centers. The value to industry of federally funded university research is even greater than previously suspected. A survey by Carnegie-Mellon University concluded: "The conventional view holds that the short-term impact of university research on industrial R&D is negligible except in a few industries. Accumulating evidence suggests that we revise this perception....university research provides critical short-term payoffs in some industries (such as pharmaceuticals) and is broadly important in numerous industries" (Cohen et al., 1994). One survey of companies and academic researchers showed that academic research has made significant contributions to a range of products, and that industry and government have played complementary roles in funding this work (Mansfield, 1995). At the same time, industry-university collaboration is not always smooth, and it is important not to oversell the direct and short-term payoffs.[15]

[14]Industry support has increased from $123 million in 1976, about three percent of total university research, to over $1.5 billion in 1996, almost seven percent of the total (NSF, 1998).

[15]Some of the barriers and issues in industry-university collaboration are discussed in Chapter 3. A forthcoming study by the National Academy of Engineering is exploring the contributions of academic research to the performance of several specific industrial sectors.

One example of a long-standing university-industry partnership examined during the course of the study is the Semiconductor Research Corporation. SRC was created in 1982 when the semiconductor industry saw the need to prepare more students for careers in industry by funding silicon-related research at universities. Today, SRC's 13 full members and other participants invest $35 million a year in university research.[16] In 1997, SRC provided support to 700 students at 44 universities. According to Gordon Moore, cofounder of Intel, the "consortium's funds have been successful in keeping several major universities engaged in research that is immediately germane to the integrated circuit industry" and "the industry has probably leveraged more than two to three times the money it has invested in the SRC, some $200 million over a ten-year period" (Moore, 1996).

Partnerships involving government

The federal government has played an important role in fostering intersectoral cooperation and partnerships in research. One such partnership is SEMATECH, a consortium of private firms set up with government support to strengthen the domestic chip-manufacturing industry. Since SEMATECH was founded in 1987, U.S. firms are once again world-class competitors. Although the turnaround cannot be attributed only to SEMATECH, it did succeed in showing that competitors can collaborate to their mutual benefit. After a decade of operation and $800 million in federal funding, it now plans to continue without further federal support (Roos et al., 1998).

Another government-sponsored partnership, the Engineering Research Centers (ERC) program, was established in 1985 by the NSF at least partly in response to the concern that U.S. industrial competitiveness was declining. The program has sought to increase interactions between universities and industry, including the pursuit of interdisciplinary research, and to offer students a broad understanding of how products move from laboratory to market. According to one study (Ailes et al., 1998), the outcome of most value to participating firms is "knowledge exchange"—access to new ideas and people. Firms perceived ERC students as better prepared than their non-ERC-educated counterparts.

An example of a successful ERC is the Data Storage Systems Center (DSSC). In the early 1980s, there was a dearth of university research relevant to the disc drive industry. In response, Mark Kryder, a professor at Carnegie-Mellon University, gained industry support for a collaborative research center. The DSSC was designated an ERC in 1990 and it has continued to contribute to maintaining U.S. capabilities. As a result of this program, there has been a significant increase in Ph.D.s graduated in this field, and students now are better prepared to make an immediate contribution to industry upon graduation (McKendrick, 1997).

An overseas model for government-industry collaborations is the Fraunhofer Society, formed in Germany in 1949, which now runs 46 institutes (including 5 centers in the United States) to do applied research for industrial clients, primarily

[16]See the SRC web page (www.src.org).

in mechanical engineering and microelectronics. Each institute, subsidized by government and organized internally as a profit center, makes its results available to both industry and the public. An important element of technology transfer is patent policy. The institute tends to register the patent itself, awarding an exclusive license to the industrial partner only for a particular application. The institute then may license the technology to another company for a different application (Abramson et al., 1997).

In recent years, the U.S. federal government has participated in a number of collaborative research programs with industry and/or universities. Two major government-industry partnerships are based on private-sector initiative and investment. The Intelligent Transportation Systems Program, established in 1991 by the Department of Transportation, seeks to enhance the capacity of the surface transportation system while reducing its social costs. The National Information Infrastructure project is the product of the deregulation of the telecommunications industry and the success of the Internet. The federal government sees its primary role as catalyst and consensus seeker.

The Advanced Technology Program (ATP) of NIST in the Department of Commerce seeks to strengthen the civil technology base and to support pre-competitive technologies on a cost-shared basis. Its goal is to create industrial technology that is deemed too risky for firms on their own, but which has the potential to benefit not only the firm but also the nation if developed. The technological value of the program has been difficult to assess, although it functions well administratively. ATP remains politically controversial (Hill, 1998). Some analysts argue that programs like ATP and the Small Business Innovation Research (SBIR) program may displace industry funding by supporting projects that industry would have undertaken without federal help (Wallsten, 1997). Others believe that ATP, SBIR, and other programs that fund companies can play a positive role if the possible economic impacts of proposed work are considered carefully, and the results evaluated (Jaffe, 1996).

THE CAPITALIZING ENVIRONMENT

Contrary to common assumption, capitalizing on research is neither costless nor automatic. For better or worse, if there is no incentive to transform an idea into a useful process or product, it will not happen. Sometimes the incentive is apparent market value, but often that value must be mined and extracted by hard work and adequate funding. Box 2-2 lists some of the policy changes that have affected the environment for capitalizing. Although assessing the impacts of these changes comprehensively was beyond the scope of the study, a number of them have had effects on capitalization in particular fields examined by the working group.

Capitalizing usually works best when there is wide diffusion of information, a consistent and supportive regulatory environment, and easy movement of people between institutions. These features are part of a web of institutions, regulations, markets, and laws that enable the ownership of rights, the development of tech-

BOX: 2-2
Examples of policy changes affecting capitalization

1978-1979: A significant reduction in the capital gains tax and changes in rules that allow pension funds to be invested in venture capital funds revitalized the venture investing environment.

1980: Passage of the Bayh-Dole Act allowed agencies to license exclusively patents of inventions in which the agencies had invested.

1980: Passage of the Stevenson-Wydler Act encouraged university-industry collaboration.

1982: Creation of the U.S. Court of Appeals for the Federal Circuit as a unified appellate court for patent infringement cases contributed to more uniform enforcement and strengthened intellectual property protection.

1982: SBIR program was launched by federal research funding agencies.

1984: Passage of the National Cooperative Research Act softened the risk of civil antitrust prosecution of firms collaborating in R&D. The act was a response to the belief that Japanese consortia of competing firms held a competitive advantage over U.S. firms.

1986: Passage of the Technology Transfer Act gave incentives to government agencies and national laboratories to enter into cooperative R&D agreements.

mid-1980s: The NSF initiated ERCs and Science and Technology Centers to promote interdisciplinary research in universities; industry participation is required.

1987: SEMATECH was launched with industry and DoD support to perform collaborative semiconductor-related R&D.

Late 1980s and early 1990s: At the height of U.S. concerns over competitiveness, the ATP was launched, and several federal agencies and private-sector groups produced "critical technology lists." Several public and private initiatives (Civilian Technology Corporation, U.S. Memories) were proposed but never launched.

1993-1994: The rapid expansion of ATP and other civilian technology programs was followed by a backlash against the growing federal role.

SOURCE: Compiled by COSEPUP staff.

nology, and the ability to secure adequate returns on investments. Capitalization also is fueled by a pool of private capital and a culture of entrepreneurs who have economic freedom, confidence in the economic environment, and financial incentives to take the risks associated with innovation.

An important economic feature of the capitalizing environment is the regulatory and trade environment, which allows entry by new firms and high levels of interfirm competition. These policies reduce the market power of dominant firms—especially in the semiconductor, computer hardware, and computer software industries—and support diffusion of intellectual property to a degree not seen in Europe or Japan (Mowery, 1996).

An entrepreneurial culture

In the development of the Internet, biotechnology, and other rapidly growing areas of capitalization, the interchange of people between universities and industry has been especially important. An environment allowing the free movement and communication of key individuals has allowed for the creation of networks of individuals, an "invisible college" of expertise.

The community of ambitious investors, entrepreneurs, scientists, and engineers who form these networks is viewed as a national asset (COSEPUP and STEP, 1999a). The "Silicon Valley culture" that tolerates risk and even failure is vital in allowing innovative ideas to flourish. An open culture facilitates access to ideas, people, and capital, even among competing firms. In the broader business culture, the ability to revitalize companies that have stagnated or have been challenged by global competition helps to maintain productivity and agility.

These forces come together in what Jane Fountain (1998) calls a "high-performing industry network," of which Silicon Valley is the paradigm. Firms are characterized by delayering of the chain of command, cross-functional teams, fluid division of labor, flexibility, high capacity to absorb innovation, and organization by business unit rather than function. Such a network typically has an outstanding nucleus of research and education at its center. One expert suggests that, in 1994, 100 Stanford-related companies accounted for about $53 billion out of a total of approximately $85 billion (over 60 percent) of the revenues of Silicon Valley companies (Gibbons, 1997).

A particular strength of the U.S. capitalizing environment is the availability of private financing. Several components of this system are (COSEPUP and STEP, 1999a):

- **Venture capital institutions:** The most prominent is the professional venture capital firm, which typically functions in partnership with entrepreneurs. The people who staff these firms are professional managers who invest funds from corporate and public pension funds (43 percent), endowments and foundations (21 percent), corporations (19 percent), and other investors.[17]

- **Entrepreneurs:** Central to the culture of innovation are those who create and drive new businesses. Venture capital funds and other investors look for particular qualities in these people, including knowledge of markets, intuition, interpersonal skills, willingness to take risks, independence, a strong desire to own their own business, and an ability to learn and bounce back from failure. The role of scientists and engineers as entrepreneurs was covered earlier.
- **Angels:** These individual investors are often entrepreneurs who have achieved financial success in a prior venture. According to one estimate, of the roughly two million self-made, high-net-worth individuals in the United States, approximately 250,000 are angels (Sohl, 1997a,b). They invest $10 billion to $20 billion each year in over 30,000 ventures (vs. $3 billion to $4 billion invested annually by about 500 professional venture capital funds in about 3,000 companies).

Other elements of the capitalizing environment

Competition, the flow of knowledge, and the protection and management of intellectual property are important and complementary elements of a favorable environment for capitalization, as illustrated by several historical examples.

Many innovations in microelectronics originated at AT&T Bell Laboratories. Because AT&T operated as a monopoly under a consent decree until the early 1980s, it was forced to license its inventions on reasonable terms and was barred from competing as a merchant semiconductor producer. This resulted in a flow of knowledge and expertise that seeded the growth of the U.S. semiconductor industry. Balancing the need to ensure competitive markets with the danger of constraining the innovative power of strong companies is a continuing challenge for the United States and other countries.

Another advantage in the U.S. capitalizing climate is a system of patent laws that gives incentives to innovators while promoting the diffusion of knowledge. Intellectual property protection is critically important in all high-technology industries, although the role of patents varies widely by field. They often play a direct role in competition in the pharmaceutical, biotechnology, and chemical industries. In other industries where technology changes rapidly, such as semiconductors and computers, firms may be in a position to profit handsomely simply by exploiting a head start. In these industries, intellectual property protection is often important as a means for firms to establish and sustain their technological foundation or as a lever to prevent piracy.

[17]During the 1997-1998 period, investments by venture capital funds were increasing rapidly. For example, the Price Waterhouse Coopers Money Tree Survey reported that 760 companies received $3.7 billion in the second quarter of 1998, with about 70 percent of these investments in high technology companies. See (www.pwcglobal.com).

CAPITALIZING IN A GLOBAL CONTEXT

One steady trend of the past several decades is the globalization of science and engineering research activities and capability to capitalize. This study examined the international aspects of capitalization, with the goal of generating insights on three issues. First, how effective is the United States at capitalizing on science and engineering research compared with other countries, and does it matter? Second, what can we learn about capitalization from cases in which one country leads in research but where there is a failure, delay, or geographic shift in capitalization? Third, what is the benefit of supporting expensive cutting-edge research in a world where knowledge, investment, and other assets are increasingly free to move across borders?

Does the capitalizing effectiveness of the United States versus that of other countries matter?

One issue that has been debated over the past 10 years is whether the United States is effective at capitalizing on research investments compared with other countries. Some have argued that firms based in Japan and elsewhere have been nimbler at commercializing the results of U.S. research than U.S.-based firms. This is a complex issue that the working group explored in some depth (see Appendix A for examples).

Assessing the benefits and costs to the United States when firms in other countries commercialize U.S. research is a complex exercise. In the case of significant new products such as the VCR and flat panel displays, U.S. industry and workers have not gained the income and other benefits that would have resulted from U.S. production. However, U.S. consumers have benefited from the availability of superior products. As discussed later, U.S.-based firms have capitalized on foreign research in a number of cases, demonstrating the broad value of free information flow.

Still, a consistent pattern in which U.S. researchers make valuable new discoveries, and then foreign firms jump ahead to develop and commercialize them, would reveal a need for new approaches. Fortunately, the examples examined by the working group show that this is not generally the case today.

In several important product categories, Japanese firms have taken technologies that had been demonstrated or commercialized by non-Japanese companies and created profitable new markets. These include the oxygen steel-making process (developed in Austria), the numerically controlled machine tool (developed at MIT and first commercialized by U.S. companies), and liquid crystal displays (prototyped by RCA; see Appendix A). The working group did examine one case in which U.S. research was turned directly into products overseas: the field of fuzzy logic, which emerged at the University of California at Berkeley and was applied in Europe and Japan (see Appendix A). On the other side, U.S. companies also have capitalized on research breakthroughs and even products developed elsewhere, such as MRI, monoclonal antibodies, and the jet engine.

Although the United States has been very effective in taking research to the first demonstration or product, in the 1970s and 1980s some U.S. companies and industries clearly faltered in later stages of the process in some fields—notably in semiconductors, automobiles, and consumer electronics, where Japanese companies forged ahead through superior product development, manufacturing, and marketing. Yet it is important to remember that capitalizing on research is a dynamic process. A technique that gains market leadership in one decade may not be effective in the next. U.S. industries were surprised by Japanese market successes in the 1970s, but they learned important lessons and since then they have become far more efficient. This year, when the United States ranks first in the world in competitiveness, Japan has fallen to eighteenth position (IMD, 1998). Of course, this situation could reverse itself again in the future.[18]

Since the 1980s, many U.S. companies have devised ways to capitalize on research by bringing their products to the marketplace more swiftly. Two examples of corporate retooling—Motorola's revised manufacturing process and Chrysler's new system of product development—illustrate how the application of a new strategy can pay off.

In the mid 1980s, Motorola faced severe competition in the cellular phone business. A challenge by the company's cellular chief, Ed Staiano, to rethink the entire manfacturing process, led to a new "dedication to quality, product leadership, global reach, strategic and organizational flexibility, and a management style that encouraged initiative at every level...." (Lester, 1998). By sharpening its marketing focus and improving the quality of its manufacturing process, Motorola became the second-largest manufacturer of cellular infrastructure equipment and for a number of years was the world's leading producer of cellular telephones. Like all international companies, Motorola continues to face challenges in global competition in the cellular phone market and in other areas.

The Chrysler Corporation benefited from increased attention to product development, manufacturing and marketing. In the early 1990s, profits and market share languished and Chrysler had no competitive entries in the small-car market, which was dominated by Japanese companies, and in other important segments. Chrysler increased the introduction of new models and changed its process of product development to achieve quicker timelines and greater efficiency. The introduction of autonomous "platform teams," consisting of all the people needed to design and produce a new car (manufacturing, purchasing, marketing professionals, hourly manufacturing workers) improved teamwork, saved time, and reduced last-minute changes (Lester, 1998). The new cars proved popular, and Chrysler has achieved impressive gains in market share and financial performance since 1992.[19]

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[18]For an assessment of the factors underlying U.S. resurgence in a number of industries, see STEP (1999).

[19]In 1998, Chrysler and Germany's Daimler-Benz announced that they were combining in the largest industrial merger in history.

Despite the overall positive performance of the U.S. economy during most of the 1990s, it is clear that the United States will continue to face economic challenges [see NRC, 1999]. As discussed earlier, science and technology is a dynamic arena, and capitalizing on science and technology advances requires constant adaptation to change.

What can be learned from examples of failure, delay, and geographic shifts in capitalizing?

The working group became aware of several examples of failure and delay in capitalization, as well as cases in which breakthroughs made by one country were capitalized upon by another. These examples provide insights into the capitalization process and the elements necessary to take advantage of research. Among the examples studied, there were several general reasons for failure, delay, or geographic shifts.[20]

- **Entrenched existing technologies**: Excellent research cannot be capitalized upon in some applications because an existing technology already performs the same function. The new approach cannot overcome barriers of cost and investments in infrastructure that support the existing technology. This applies to several applications of optical sensing, and probably to U.S. slowness to utilize fuzzy logic.
- **Need for complementary advances**: Capitalization may be delayed because of a need for complementary advances across a number of fields. Speech recognition is a good example. In the 1980s, after several decades of long-term industry and government research, hardware and software advances combined to produce an environment in which applications could develop and expand.
- **Lead users of research are absent or located in other countries**: Examples in which a product developed in one country is capitalized upon by another include NC machine tools and flat panel displays. This appears to occur when an industry concentrated in the capitalizing country has an appropriate infrastructure and a pressing business need that can be advanced by applying the research. Similarly, capitalizing may be hindered by weak links between researchers and lead users. This appears to hinder the application of research on cognition and learning in education.
- **Lack of flexible human resources and a weak environment for launching science- and technology-based companies**: In several instances, the United States has been able to capitalize on research breakthroughs achieved elsewhere, particularly in the biotechnology and biomedical areas. In fields such as monoclonal antibodies, where new compa-

[20] This list is meant to be illustrative and not comprehensive.

nies played a significant role, the presence of a favorable environment for starting new companies and a pool of trained and mobile people have been important contributing factors.

- **Weak cooperation between sectors**: In several industries in which Japan has enjoyed success in the past, such as oxygen steelmaking and semiconductors, cooperation among companies and between government and industry appears to have played an important role. Likewise, examples of U.S. industry resurgence in semiconductors, data storage, and other areas have been associated with significant efforts to forge greater interfirm and intersectoral cooperation, such as SEMATECH, SRC, and DSSC.

Do national investments in a global knowledge base make sense?

One of the key insights underlying the economic study of scientific and technological advances is that private firms tend to invest less in research than is optimal for society as a whole. This is because research activities create large spillover benefits that the investing firm cannot appropriate completely (Nelson, 1959). The tendency for R&D activities to produce spillovers outside the performing organization is a strong rationale for public support.

As discussed further in Chapter 3, firms and governments alike face pressure to focus their science and technology investments in areas most likely to produce clear benefits in the short term. At the same time, as technological capability becomes globalized, multinational firms are better able to capitalize on important developments wherever they occur. Does this imply that the fundamental science and engineering research that is least appropriable by individual firms is an international "free good"? Does the key to success for firms and nations lie in exploiting the world's basic research while performing as little as possible themselves? Will national governments underinvest in fundamental research in the future?

Although these are complex questions, the literature on the economics of innovation and the working group's observations suggest that support for fundamental research is a very worthwhile national investment.

As noted earlier, capitalization is not a costless activity. Nathan Rosenberg (1990) has observed that firms are often unable to capitalize on external basic research advances unless they are performing basic research themselves. Judging from examples examined by the working group, such as catalysis and monoclonal antibodies, this appears to hold true at the national level as well. It appears that organizations and countries must make a significant contribution to the world's stock of scientific and technological knowledge if they hope to take advantage of cutting-edge developments themselves.

Also, there is evidence that science and technology activities are not as globalized as some believe (Pavitt, 1991; Callan et al., 1997) Although the subject deserves additional examination, it appears that most national technological systems are still relatively self-contained. Further, firms that do a large percentage of their R&D outside their home country, as do firms based in Holland and Switzerland, may be best positioned to take advantage of increased globalization.

Finally, it is apparent that investments in research help to create many of the assets that are essential to capitalization. Perhaps foremost among these is human capital, in the form of educated scientists and engineers who perform cutting-edge research and also play important postresearch roles in capitalization. Sustaining U.S. research capabilities, including the physical infrastructure for research and advanced education, at the same time strengthens the stock of human capital. This is a national asset that is far less mobile than financial capital or disembodied knowledge transmitted by research papers or the Internet.

In short, it appears to be more difficult for countries to "ride free" on basic research than is sometimes assumed. Recently, Japan, Korea, and other countries that have enjoyed success in capitalizing on foreign technology in the past have moved to establish basic research institutes and to strengthen advanced science and engineering education. This may reflect a realization that efficiencies in manufacturing and marketing are not in themselves sufficient for effective capitalization at the leading edge of science and technology [see Department of Commerce (1997)]. Exploitation of proven foreign technologies has allowed countries in Asia and elsewhere to develop rapidly. As incomes and wealth grow, however, it appears that more advanced capabilities are required for countries to continue catching up or even stay in place. Just as U.S. companies and institutions learned from Japan's superior manufacturing practices, other countries are adapting U.S. best practices in capitalizing on science and technology to their own circumstances (Mathews, 1997).

The United States enjoys success in capitalizing on investments in science and technology because of its investments in research, its favorable environment for capitalizing, its outstanding human resources, and its ability to forge cooperation among the industry, university, and government sectors. None of these factors is sufficient in itself, and it appears that all four are increasingly complementary and mutually reinforcing. Chapter 3 describes some of the challenges that the United States faces in maintaining and improving its ability to capitalize in the future.

Chapter 3

ADAPTING TO NEW CHALLENGES

Between World War II and the collapse of the Soviet Union, the U.S. economy operated in an environment characterized by military and economic competition. Federal research and development (R&D) investments, especially through the Department of Defense (DoD), dominated research spending through much of this period (representing about two-thirds of the national total at their high point) and many high-tech advances were defense spinoffs. Product life cycles were measured in years, and allowed ample returns on industrial research investments. Financial markets were relatively patient, and considered a wide range of factors in determining a company's health.

Much has changed, and the capitalizing process must continue to adapt. Commercial interests have replaced military procurement as the driving force of technology; industry now funds two-thirds of the national R&D effort. National competition is giving way to growth in international business and multinational mergers; global outsourcing and supply networks often blur patterns of ownership. Unprecedented mobility of capital and technology bring advanced R&D capabilities to more nations. Investors demand quarterly profit growth, and the marketplace demands shorter product cycles. Both industry and government seek to cut spending and balance budgets.

Chapter 2 identified the factors underlying U.S. strength in capitalizing on investments in science and technology—a diverse portfolio of cutting-edge research across all fields, a favorable environment for capitalization, superior human resources, and effective cooperation across sectors. The U.S. science and engineering enterprise faces new challenges that will require adaptation in all of these areas.

THE ENVIRONMENT FOR INVESTING IN SCIENCE AND TECHNOLOGY

One result of these changes, especially in industry and federal agencies, is a growing incentive to curtail research whose payoffs are potentially high but whose results cannot be appropriated exclusively by the sponsor. There is support in Congress for basic research, but also a desire for research whose results can be predicted and measured. Agencies are required to emphasize performance measures, accountability, and short-term, practical results. Congress, through the Government Performance and Results Act of 1993, requires federal R&D agencies to submit strategic plans, performance plans, and annual reports demonstrating how their research contributed to those plans. Some in the research community are concerned that this requirement will favor short-term, low-risk research projects whose results are easily measured over long-term, high-risk research whose evaluation is more problematic [see COSEPUP (1999b)].

Within this environment of growing pressure for measurable results and accountability, individual fields face particular challenges. For example, in information technology a recent report by a panel of experts asserts that government agencies are not providing sufficient support to high-risk, long-term research that will lead to future innovations (President's Information Technology Advisory Committee, 1998). Federal funding has been flat and increasingly focuses on short-term problems. These nearer-term investments, such as the Next Generation Internet (NGI) initiative, are aimed at ensuring the robustness of the Internet and are certainly essential.[1] The information infrastructure is important to the nation in the same way that its bridges and highways are. Yet, it is just as essential that longer-term, higher-risk research that will contribute to future radical advances also is funded.[2]

One of the strengths of university research and the traditional central labs of industry has been the vibrancy of doing fundamental and applied research in close proximity. Losses from either category dilute the intellectual climate. During panel discussions and workshops, participants told the working group that universities and industry are doing too little basic research in fields such as networking, catalysis, and semiconductors.

The changes in industry are also dramatic. Large companies that traditionally supported rich programs of long-range research have been pressured to cut back to maintain competitiveness (Nelson et al., 1996). Many have reduced their research organizations, have learned to acquire ideas and technology from outside the firm, and have adjusted their sights toward nearer-term goals. Large manufacturers are giving suppliers greater responsibility for engineering and design work, and some medium-size firms that specialize in particular technologies are emerging as the key sources of innovation. The large pharmaceutical companies rely on more agile biotechnology companies for new ideas, and few of the fastest-growing computer hardware or software companies founded in recent years support centralized research facilities.[3] Although it would be a mistake to overestimate the scale of long-term basic research that industry performed in the past, this work has produced many

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[1]See www.ngi.gov for an overview of NGI.

[2]In an area such as networking, where existing strong products and standards such as TCP/IP exist and are difficult to displace, private firms may be reluctant to fund research on radical new approaches. This makes the federal role in supporting this work even more important.

[3]Dorothy Leonard-Barton and John L. Doyle (1996, p. 181), describe Chaparral Steel, an innovative U.S. minimill, as integrating research with development. They quote the CEO, a former R&D director with a Ph.D. in metallurgy from Massachusetts Institute of Technology, as saying that research laboratories are idea graveyards "not because there are not good ideas there, but because the good ideas are dying there all the time."

important innovations over the years. In general, the current trend is toward shorter time horizons and greater focus on specific products in industrial R&D.

Because they can no longer call on internal labs to answer research questions, many industries have formalized their dependencies on outside sources. Some examples include the following:

- In the aircraft industry, competitive pressures and defense-related cutbacks in federal R&D funding are forcing a shift in focus from high-risk technologies to demands from airline customers for lower cost of ownership. In recent years, industry has reaped the benefits of past R&D investments in computational fluid dynamics, materials, and computer-integrated design and manufacturing. Long-term research in this industry traditionally has been funded by government, and with tight funding, companies are focusing R&D spending on short-term research and product development. The leading U.S. manufacturer, Boeing, has drawn on its component suppliers for R&D. Suppliers, in turn, are outsourcing more R&D to their subcontractors.
- In the auto industry, rising development costs are raising overall R&D expenses, but investment in long-term research has fallen. Virtually all R&D is tied to specific product goals, including incremental improvements. To supplement internal R&D, the Big Three automakers rely more on suppliers, cooperating with each other through the United States Council for Automotive Research consortium, and increasing interactions with the government, especially DoE, through the Partnership for a New Generation of Vehicles. They look to universities for short-term engineering needs, long-term research in the physical sciences, and well-trained students.
- In the chemical industry, the research structure is shifting to accommodate short-term business unit needs rather than longer-term, corporate objectives. Industry is forming more partnerships with both universities and federal laboratories and using these partnerships to leverage their spending on precompetitive research (Council on Competitiveness, 1995).
- Across the spectrum of industries, major corporations have reduced, sold, or closed their research facilities. During the early and mid 1990s, IBM cut and refocused its research spending (Ziegler, 1997). RCA's Sarnoff Research Center, the source of pioneering research in video, liquid crystals, lasers, and other fields, was spun off to SRI International following GE's acquisition of RCA, and converted to contract research.

It is important to recognize that pressures on government for greater accountability and on firms for greater focus and customer orientation are producing many positive results, and are occurring in countries around the world. Decentralized technology strategies are not new developments in U.S. industry. Intel, for example, decided early not to maintain a central research laboratory, choosing instead a strategy that it calls "minimum information" (Moore, 1996). It has thrived by making incremental changes to existing technologies, with extremely short times between development and manufacturing, and low research expenses. There are also counterexamples: Hewlett-Packard tripled its R&D budget in the 1990s, and a few software companies, notably Microsoft, are establishing corporate labs.

A countervailing tendency is the growth of research funding by private foundations. Although foundations long have played a key role in supporting the U.S. science and engineering enterprise, since World War II their contributions have been dwarfed by the growth of federal government and industry investments. In recent years, vast wealth has been accumulated by individuals and foundations because of the rise in the stock market. The emergence of angel investing, discussed in Chapter 2, is one example of how this wealth is channeled into capitalization. In the future, foundations and wealthy individuals can be expected to play a growing role in directly funding research and supporting universities and research institutions. One example is the Howard Hughes Medical Institute, which provided over $400 million in 1997 for medical research, grants, and special programs (Howard Hughes Medical Institute, 1997).

Still, ongoing changes will complicate the task of ensuring that the public and private sectors provide sufficient funding for a diverse national portfolio of science and engineering research. A primary concern is whether investments in long-term research, especially in fields of obvious national importance, will be adequate.

EDUCATION FOR THE LONG TERM

Universities face the challenge of preparing students to be "employable for a lifetime" and of preparing them to enter the current job market upon graduation. These goals are both complementary and competing. It is inevitable that the supply of graduates will not perfectly match employer demand, especially in emerging fields where new or multidisciplinary skills are prized (see Box 3-1).

Currently there is heavy demand for skilled employees in the field of information technology. CEOs of leading companies say that worker shortages are preventing the development and marketing of new products, lowering sales, and costing the country hundreds of thousands of jobs (Lerman, 1998).[4] Hiring pressure is so strong that the industry is hiring predegree students and junior faculty out of the universities at attractive salaries.[5] At the same time, a decrease in university research funding for these fields has reduced the number of graduate students being trained.

The federal government and the private sector can both play a major role in helping institutions to meet new demands for trained scientists and engineers. Personnel exchanges can bring nonacademic people to the campus and allow stu-

[4]This is a very complex issue, and the information technology labor market is highly diverse in terms of the training and experience levels needed for different sorts of jobs.

[5]Note that data on median salaries of scientists and engineers by degree level show that engineers and computer scientists receive a relatively low premium for earning a Ph.D. vs. a Master's degree (10 and 14 percent, respectively), whereas life scientists (32 percent) and physical scientists (25 percent) earn a higher premium (National Science Board, 1998).

BOX 3-1
Challenges for advanced research and education: Networking and bioinformatics

Networking

During a recent workshop, a panel of experts in networking research described a trend: Little long-term research is being done in computer networking, either in universities, industry, or government labs.[a] The next wave of technical and systemic challenges to networking may find the field unprepared to deal with them.

The era of networking began in the late 1960s, when it became desirable to share computing facilities among users. The problem of how to connect different computers, and eventually different networks, was solved over a period of several decades by a small, informal community of researchers who shared resources and an ethic of openness and cooperation. Many of the groundbreaking advances were funded by the Advanced Research Projects Agency/DoD and NSF, through the universities and a few private firms.

The networking industry has grown rapidly during this decade. Job demand has become so strong that faculty with applications-oriented networking expertise are being drawn out of the universities into stimulating and well-paying positions in the private sector, and many students are joining them in industry rather than receiving advanced training.

The departure of networking faculty from universities means that students have difficulty finding mentors and acquiring experience in problem selection. Many faculty who do remain are those who study theoretical rather than technological aspects of networking, because theory often is more highly rewarded by the academic world. Compared to theory, practical networking is interdisciplinary, collaborative, and "messy"—that is, the skills required to solve problems of connectivity and communication may extend far beyond engineering to include marketing, politics, certain aspects of mathematics (queuing, logic, probability), and verbal and collaborative skills.[b] As one panelist put it, "There is too much to fit into one brain."

Like the universities, private firms are doing little fundamental systems research. Networking firms are growing so rapidly that they have little interest in or time for long-term research; innovation is driven primarily by product development problems. Companies that need new techniques often acquire

[a]National Academy of Engineering (NAE)/COSEPUP Workshop on the Role of Human Capital in Capitalizing on Research, Irvine, Calif., January 20-21, 1998. Panelists included Robert Sproull, Sun Microsystems, Inc. (moderator); David Farber, University of Pennsylvania; Deborah Estrin, University of Southern California; and Brian Reid, Digital Equipment Corp.

[b]Although information systems design has always required attention to these issues, they are increasingly relevant to lower-order design tasks.

Box 3-1 continued

smaller firms that already have developed them. Panelists lamented the lack of a strong industry presence not only in performing fundamental networking research, but also in setting the research agenda. Nor is the government any longer taking the lead in supporting research and guiding the agenda, as it once did.

The engineering aspects of networking face large challenges in coming years: how to make the transition from a dedicated to a shared infrastructure, how to better meld the networking industry with the telephone industry, how to design optical network systems, how to link embedded processors, and, in general, how to cope with the explosive growth of the industry. Some of these problems require not only engineering experience, but also varying levels of expertise in marketing, consensus building, political science, and urban planning; the installation and linkage of network systems depends on leaders who possess a range of technical, political, and "people" skills.

One model that may prove useful for companies and universities involved in networking is the Semiconductor Research Corporation (SRC), an industry partnership that funds university research and student training, described in Chapter 2.[c] Student internships in industry and mentoring of students by industry researchers are important components of SRC programs. When the SRC was formed in 1982, a shortage of trained researchers threatened the long-term health of the semiconductor industry. Although the situation is not directly analagous to the situation in networking today, SRC illustrates how competitors can come together to create assets important to all.

Bioinformatics

This new field, which spans mathematics, computer sciences, chemical engineering, the life sciences, and health care, is fueled by federal support for mapping the human genome and the need for mathematical modeling to produce new drugs in the biotechnology and pharmaceutical industries.[d]

Currently, there is a shortage of qualified people to work in this field. A recent analysis suggests that too few trained students are graduating to meet

continued

[c]See SRC's web page at www.src.org.

[d]This box is based on a discussion at a workshop organized by NAE and COSEPUP on the Role of Human Capital in Capitalizing on Research, January 12-13, 1998, and a background paper prepared for the workshop (Stephan and Black, 1998). Panelists included Stephen Clark of Amgen, Bernard Palsson of the University of California at San Diego, Paula Stephan of Georgia State University, and Carlos Zemudio of Axiom Biotechnologies.

Box 3-1 continued

the needs of industry, and that junior faculty are leaving universities for challenging, well-paying positions with biotech and pharmaceutical companies.

At the same time, many qualified Ph.D.s in the life sciences are taking longer to finish their degrees and are undertaking multiple postdoctoral positions because of a shortage of permanent tenure-track positions (NRC, 1998). What accounts for this inconsistency?

Several factors influence the availability of human resources in these fields. One is the research funding system, in which scholars seek to establish themselves as principal investigators (PIs) overseeing their own laboratories. Attracting superior graduate research assistants increases the productivity and quality of research, allowing the PI to secure research funding. In this environment, work in emerging interdisciplinary fields such as bioinformatics may be difficult to initiate. Establishing new educational and research programs in bioinformatics would require collaboration among computer science departments, biology departments, and medical schools. In a funding environment emphasizing research grants to PIs, incentives for such collaboration may be weak.[e]

Further, in the research culture of the life sciences, an M.S. is not seen as an acceptable terminal degree. Research and education in the life sciences therefore may be less responsive to trends in the nonacademic job market than other fields, such as engineering.

Finally, it may be difficult to "retool" life scientists to work in bioinformatics by having them take a few computer courses. Some experts argue that students who choose to study biology tend to have a lower level of interest or talent in mathematics. Yet others argue that such retooling can be done.

Some workshop participants pointed out that the lack of human resources in this area is understandable, since bioinformatics has emerged only recently. To several panelists, developing new educational programs that impart skills in computing and life sciences, from the undergraduate level onward, is the key long-term challenge for universities and other stakeholders.

[e]Several experts who have attempted to secure funding for new centers or programs in bioinformatics reported experiencing difficulties in the peer review process, which they believe partly reflected an inability for some reviewers to consider the context beyond their own disciplines.

dents to meet nonacademic scientists and engineers, helping both students and faculty understand nonacademic working environments and job opportunities.

A basic strength of the university is its disciplinary structure, which allows students to immerse themselves deeply in a well-defined subject. At the same time, the traditional boundaries of a discipline may present a challenge to students who want to investigate emerging fields. To arrange a program in bioinformatics, for example, a student may have to take computer science courses in the school of engineering, mathematics courses in the school of arts and sciences, and biology courses in the life sciences department and the medical school.

The structure of financial support for graduate students can affect their ability to investigate emerging fields. A student who is supported by a research assistantship makes a commitment to contribute to a specific program and may lack the ability to pursue broader study. A student supported by a fellowship or direct grant may have more flexibility to study subjects in multiple fields and do research in a less traditional area.

Of course, U.S. educational institutions will need to broaden their approaches to ensure that the United States has the human resources needed to capitalize on science and technology advances in the future. This study focuses on research universities because of their central role in advanced research and education.

Overall, U.S. research universities are remarkably successful institutions. Their challenge is to maintain traditional strengths as they respond more flexibly to emerging education and training needs. Prior to World War II, the university focused on the codification of applied science and engineering expertise and the development of new fields of inquiry and training in response to industry requirements (Rosenberg and Nelson, 1994). As the university research enterprise grew over the postwar decades, and institutions came to rely on federal funding to maintain their excellence, filling the ranks of the professoriate became a key task for advanced science and engineering education.

COSEPUP's (1995) report on graduate education in science and engineering called on educators to put greater emphasis on training students for nonacademic careers and suggested that greater diversification in federal funding mechanisms could contribute. Since the release of that report, federal agencies have developed new initiatives that move in this direction.[6] Continuity is a strength of the U.S. research university, and it probably would be impossible to eliminate supply-and-demand mismatches in science and engineering labor markets. Nevertheless, the current shortage of talent in bioinformatics and the career difficulties being experienced by young life scientists should indicate to universities and federal agencies that a coordinated response is required.

[6]One example is the National Science Foundation (NSF) Integrative Graduate Education and Research Training program. The National Institutes of Health supports a wide range of training grants.

PARTNERSHIPS TO LEVERAGE CAPABILITIES AND RESOURCES

As science and engineering become more complex and multidisciplinary, more skills, more teamwork, and more people are required to perform and capitalize on research. As described in Chapter 2, the past two decades have seen an explosion of research collaboration and partnerships between industry, universities, and government. For example, in 1994, there were 1,000 university-industry research centers (UIRCs) on more than 200 university campuses (Cohen et al, 1994).

And yet there are barriers to more efficient functioning of such partnerships (Government-University-Industry Research Roundtable, 1999). For example, graduate students and even faculty may know little about the changing role of senior professionals in industry. Individual scientists and engineers must be able to lay out program goals, identify several options, and plan ways to capitalize on their research. They need to know how to network, negotiate, and manage a partnership with other researchers. Differences in expectations and culture can challenge students seeking careers and faculty seeking partnerships in industry. In a discussion on catalysis, several U.S. academics stated that it was easier for them to work with European-based companies than with U.S.-based companies (see Appendix A). Likewise, researchers at several U.S. companies reported greater success in structuring collaboration with foreign or second-tier U.S. universities than with the U.S. universities leading in catalysis research.

Universities and industry have different views on intellectual property rights (IPRs). Patents allow inventors a period to exploit their innovation in exchange for publication. Companies often seek exclusive rights in order to capitalize on their investment; some universities now seek control of rights as well. As in other areas of capitalization, the situation is complex and varies significantly by field. Universities differ in their attitudes toward faculty who wish to hold equity in start-up companies. An important, unresolved question is the extent to which current IPR restrictions may be inhibiting the development and application of new knowledge and, conversely, the extent to which the pursuit of profits may inhibit the progress of basic research. In short, universities are challenged to develop partnership modes that promote effective interaction with industry and complement their primary missions: education and the creation of new knowledge. In this task, the diversity of approaches among universities can be a strength of the U.S. system; not every institution needs to emulate Massachusetts Institute of Technology or Stanford.

The benefits of breaking down institutional barriers can be seen in the high-performing industry networks: Silicon Valley; Research Triangle Park, North Carolina; the Route 128 complex outside Boston; the textile firms of northern Italy; and the industrial centers of Japan. Note that the most successful of these networks depend on the proximity of competing firms. The zero-sum depiction, in which institutions gain at the expense of others, does not seem to be accurate; in these cases, joint gains are realized and advantages shared, even under conditions of fierce competition (Fountain, 1998).

The growth of partnerships between sectors over the past two decades represents a significant adaptation of the U.S. science and engineering enterprise aimed at improving capitalization. Much anecdotal evidence attests to the value of collaboration, but evaluating the effectiveness of individual programs and approaches is inherently difficult. Although SRC is considered to be very successful and has a significant track record, discussion at an NAE/COSEPUP workshop revealed that sustained efforts are required on the part of the member companies to extract maximum value. Cases of university-to-industry knowledge transfer that clearly contribute to specific products are limited (Randazzese, 1996).

In the broader context, a focused effort may be required to codify lessons and highlight the best practices of collaboration (Mowery, 1998). Utilizing such lessons, it may be possible to widen the scope of partnership activities. For example, the community of researchers who work on cognition and learning believe that they have generated a number of significant insights that could be applied to K-12 education, where the United States faces serious challenges (see Appendix A). Incorporating these insights into new teaching approaches, testing them, and encouraging their adoption in schools are activities that require focused and extensive effort. Several institutions are doing this work, but not on a large scale.

In addition, new barriers to collaboration are emerging and, as discussed earlier, old ones may be reemerging in new forms as the perspectives of stakeholders change. Continued efforts to reduce these barriers could deliver significant benefits.

Finally, as partnerships grow and change, it will be important to maintain realistic expectations about what they can and cannot do. Programs such as SRC, NSF's Science and Technology Centers and ERCs and others show that collaboration can encourage companies to fund areas of fundamental, long-term research that they would not support by themselves. However, workshop discussions during the study revealed that partnerships cannot be expected to replace the federal government as the primary funder of fundamental research in most fields.

CHANGES IN THE CAPITALIZATION ENVIRONMENT

The globalization of economic activity is straining old international relationships and demanding new trade and ownership policies. Concerns about national security must be balanced against the development of new kinds of alliances. For example, U.S. computer companies must seek exemptions from old trade laws to reimport components that they send to their Asian factories for assembly. U.S. auto companies must step nimbly around traditional import limits to sell what are mostly foreign-made cars as domestics (Brown, 1998).

Many changes alter the ways firms must do business. The highest cost—and risk—for research-based firms is in development and commercialization. Historically, they could count on long-term research from their own central labs and, in defense, a ready first customer in the federal government. Today, companies must add new options. The corporations with their functional specialization have given way to smaller, leaner organizations in which team-based structures cross functional lines, transcend hierarchical chains of command, and focus on core functions while contracting with outside firms for other tasks. For example, DuPont has doubled its spending on external R&D in the past three years, entering more than 30 cooperative research and development agreements and 6 Advanced Technology Program (ATP) grants; it expects more revenue growth overseas than at home (Guschi, 1996).

To increase access to markets and expertise, U.S. firms increasingly set up facilities abroad. Similarly, foreign direct investment in R&D by foreign enterprises is the most rapidly growing segment of U.S. R&D. (Japan-based firms alone have 98 R&D labs in North America.) To compete, firms need preferred partners, new ways to interact with universities, government, and other companies, focused communication with Washington and their state capitals, and good corporate knowledge of what they really have to offer.

At home, the climate for capitalizing on research is richer for the availability of private financing. A role for the limited-partnership venture capital firm emerged in the late 1960s, enabled by a favorable economy, stock market, and tax policy. A key reform came in 1979, when the Department of Labor changed the "prudent man rule" to allow pension funds to invest in venture capital funds. This change, plus liberal tax changes at about the same time, gave rise to the modern era of venture financing. Venture activities in the biotech field boomed in the 1980s; software and communications technologies dominated in the 1990s. The total amount of money invested by venture capitalists is small compared to other sources of finance for technology development, but the venture capital industry plays a significant role in the creation of new firms.

Individual changes may seem small, but the cumulative power of the capitalizing environment is great. This has been demonstrated dramatically since the post-World War II years, when it was predicted that open markets, growing demand, and free access to technical knowlege would close the gap between the strong U.S. economy and the economies of Japan, the United Kingdom, Germany, and France. At the time of a recent study (Patel and Pavitt, 1994), Japan and Germany had moved ahead, but the United Kingdom and France had fallen behind. Similarly, Taiwan, Korea, and Singapore had leapt ahead from very backward conditions, whereas Brazil, Mexico, and India had made less progress. Patel and Pavitt concluded that such differences in technology diffusion sprang from cultural, managerial, and institutional differences: the climate of capitalizing. Since the study was conducted, some of these conditions have changed appreciably, illustrating the dynamic quality of the capitalizing climate. Today, the capitalizing environment appears to be quite favorable. Another National Research Council study explores these complex trends in greater detail (STEP, 1999).

Although the primary current challenge in this area is to "not mess up a good thing," the study clearly shows the importance of a favorable capitalizing environment, and the speed with which conditions can change. Heightened recognition of these points on the part of the science, engineering, and policy communities can help the nation to maintain and improve this environment in the future.

Chapter 4

SUSTAINING AND ENHANCING THE ABILITY TO CAPITALIZE: STUDY FINDINGS

COSEPUP believes that our nation is well positioned to sharpen its ability to perform and capitalize on research. We have emerged from a defense-oriented era of superpower tensions into a more fluid and flexible environment in which ideas, people, capital, and goods flow more freely among nations. New technologies and new institutions, most notably small- and medium-size firms, are setting a rapid pace of innovation. Newly competitive nations are entering the global marketplace. Traditional institutions, especially universities and government agencies, are testing new policies and partnerships that will allow them to adapt to this fast-paced and open environment.

Finding 1: Capitalization on science and technology is a major national strength, although there is much room for improvement.

Capitalization appears to be quite healthy in the United States today, delivering significant benefits to the nation. Nonetheless, COSEPUP believes that there are many opportunities in every sector to improve the capitalization process. As outlined in various parts of the report, the United States has weaknesses, and complacency could lead to a decline in its strengths.

This finding contrasts with the situation a few years ago, when several U.S. industries faced serious challenges in global markets (Dertouzos et al., 1989). Foreign-based companies used superior product development and manufacturing to surge forward in high-technology industries pioneered in the United States. Pointing to continued U.S. strength in basic research, some observers were concerned that the United States was losing the ability to capitalize on its research investments, while foreign countries were reaping the lion's share of benefits (Prestowitz, 1988).

As this is written, the situation looks quite different because of two important shifts. First, many established U.S. companies and industries have improved their performance in product development, manufacturing, and marketing (see Chapter 2 and STEP, 1999). Second, a wave of new industries and companies has arisen in the United States, many of them with clear and direct links to public and private research efforts initiated several decades ago (such as the Internet and life sciences examples cited earlier). Both of these trends have benefited from, and contributed to, a favorable macroeconomic environment.

The discussion in Chapter 3 illustrates the complexity of the emerging challenges and reinforces the caution expressed in Chapter 2, against formulating policies based on overly simple models of innovation.

Finding 2: The key elements contributing to effective capitalization are

- *strong, stable funding for a portfolio of research investments that is diverse in terms of funders, performers, time horizons, and motivations;*
- *a favorable environment for capitalizing, characterized by a strong incentive structure for investors, competition in the market, and free movement of ideas and people between institutions;*
- *a skilled, flexible science and engineering human resource base that allows the United States to maintain research at the cutting edge and to capitalize effectively;*
- *mechanisms for research and capitalization that support cooperation between academic, industry, and government sectors.*

These elements increasingly interact with each other. The key challenge and task for the science, engineering, policy, and business communities will be to continue to innovate so that the elements underlying capitalization are strengthened in the face of changing circumstances. The remainder of this chapter deals with that challenge.

MAINTAINING A STRONG, DIVERSE PORTFOLIO OF RESEARCH INVESTMENTS

The rationales and mechanisms by which our institutions support research will be centrally important in the twenty-first century. The essential seedbed for capitalization is a diverse portfolio of research programs, both long term and short term, across the spectrum of major fields. An effective research policy can provide continuing, long-lasting benefits to society in the form of new insights and products and an open intellectual environment in which future generations of scientists and engineers are educated. Research investments create several of the key ingredients needed for capitalization, such as the science and engineering human resource base that transforms science and technology into practical benefits through entrepreneurship and other mechanisms.

A central role of the federal government is to monitor and assess the national science and technology investment portfolio to ensure that U.S. scientists and engineers work at the forefront of all major fields and attain clear leadership in fields deemed essential to national objectives. The federal government must serve as the "funder of last resort" to support research and capitalization efforts in fields of national importance that are not able to secure funding from other sources. This task is increasingly important in an environment where industry is the predominant funder of research and development (R&D), and both federal and industrial research funders face pressure to support work that delivers measureable, short-term results.

For example, the federal government has a unique responsibility to develop and maintain the infrastructure and technology that support modern research. For a nation to be a world leader, its scientists and engineers must have access to state-of-the-art facilities. Many of these facilities are too expensive for a single institution or even industry to support. In the case of materials research, for example, facilities and equipment in several foreign universities now outclass those at most universities in the United States. Of particular concern is the need for modern equipment for materials synthesis and processing, where the United States lags Europe and Japan (COSEPUP, 1998, p. 34).

According to workshop discussions during this study and to a recent expert panel report to the President (See Box 3-1 and President's Information Technology Advisory Committee, 1998), long-term research to generate future innovations in information technology is inadequate. In the area of applying research on cognition and learning to address the nation's educational challenges, there is significant, difficult work to be done (Appendix A). The federal government will need to recognize and respond to such funding gaps and needs.

Recognizing and responding to emerging funding needs will require new tools for policy makers. Mechanisms for monitoring and assessing the national science and technology investment portfolio are emerging, but developing these tools is a task that will require additional study and experimentation. For example, science and engineering might benefit from a continuing, regular program of assessment, or "benchmarking," for individual fields, such as those recently conducted by COSEPUP. The purpose of these assessments would be to help funders and policy makers determine appropriate levels of funding, not to set milestones or predict outcomes.

The science and engineering communities can assist in the development of monitoring and assessment mechanisms. Researchers are encouraged to determine appropriate tools to assess their own particular fields. It is tempting to try to apply universal methods of assessing the return on research investments. Some forms of research, particularly those in which a certain outcome is expected, lend themselves to quantitative evaluation. Other forms, notably internally driven, long-term research, are not assessed easily by metrics or milestones because their specific outcomes and rate of progress cannot be known in advance. The search for new knowledge also contributes to goals other than those prompting the initial research.

STRENGTHENING HUMAN RESOURCES

In recent decades, a central mission of many graduate science and some engineering programs has been to prepare the future professoriate. In accord with this mission, most U.S. graduate schools impart a solid grasp of the principles and practice of research, and of the intellectual openness of universities. However, the majority of Ph.D.s in science and engineering enter employment positions outside

BOX 4-1
A new approach to funding advanced science and engineering education

Stanford University is developing a new approach to support advanced science and engineering education. The plan is to create a $200 million endowment and to fund some 300 graduate fellowships in science and engineering. The fellowships will be given directly to students and can be transported between departments. Much of the funding will come from start-up companies. An advantage is that bright students are not punished if the department fails to attract enough fellowship money. "We see it as not only a privatization of research," said James Plummer, chair of Stanford's Department of Electrical Engineering, "but also a way to let the best and brightest seek out the most interesting projects."[a]

[a]Comments at the NAE/COSEPUP Workshop on the Role of Human Capital in Capitalizing on Research.

the academic research community—in industry, government, and teaching—where job demands and cultures may differ appreciably from those of academic research.

An important influence on how graduate students are prepared for employment is the type of funding mechanism they receive, such as fellowships, traineeships, and research assistantships. The proportion of these mechanisms has varied over time, but less in response to careful planning than to political or economic imperatives.

COSEPUP (1995) suggested in an earlier report that certain forms of financial support might allow some graduate students to gain greater flexibility in making educational choices, which could in turn allow them to select from a broader range of options and to adapt their preparation to a variety of careers. One model is the National Institutes of Health program grant, and another is the training grant recently introduced on a small scale by the National Science Foundation (NSF). Individual universities are developing their own approaches (Box 4-1). Yet little is known about how different types of grants may alter student or faculty behavior.

During a joint COSEPUP-National Academy of Engineering workshop on the Role of Human Capital in Capitalizing on Research, experts in the computer networking field stated that commercial growth is so strong that students inclined to work in industry have excellent job prospects with a bachelor's or master's degree. At the same time, the long-term academic research being undertaken in some relevant fields is becoming more specialized and "mathematical," so that students at the Ph.D. level have less opportunity to work on systems-oriented problems (see Box 3-1). The incentives for both industry and academia to do the systems-oriented research and education needed for future growth in the networking area are apparently weak. How can we ensure that our research and education investments create the necessary human capital for interdisciplinary fields in which commercial opportunities are expanding rapidly?

One member of the working group suggested that small-scale, randomized experiments could help to answer these questions (Romer, 1998). For example, some students might receive funding via portable project fellowships, whereas others might receive more traditional fellowships or research assistantships. Over time, several questions could be asked: How would students' career choices vary? Would universities respond to incentives in the form of potential tuition dollars rather than research dollars?

In the same way, one could conduct an experiment whereby principal investigators at certain institutions would apply for program grants, while investigators at other institutions would apply for traditional research grants. Would the nature of the research vary at the two groups of institutions? Would faculty promotion criteria change? What about faculty practices of teaching or mentoring? Admittedly, a controlled, randomized experiment in this area would be difficult to implement. Still, it will be important for policy makers and the science and engineering community at large to design programs in ways that the results can be evaluated.

It is desirable, by whatever mechanisms, to increase the attractiveness of careers in science and engineering. Goals that have been proposed include bringing additional real-world and teamwork experiences to the classroom, creating more industrial internships, producing more interesting courses (especially at the introductory level), and stabilizing the levels and consistency of funding policy.

Graduate students achieve richer educational experiences and greater employment opportunities through more experience in industrial labs. NSF's Grant Opportunities for Academic Liaison with Industry (GOALI) program supports university-industry linkages. Some institutions, including Massachusetts Institute of Technology, the University of Michigan, and Lehigh University, offer industrial research opportunities. From industry's point of view, well-prepared students are essential. "We believe that if we hire the right people, products and profits will follow," said a semiconductor industry executive. "If we didn't have human capital, we wouldn't exist" (Wollesen, 1998).

STRENGTHENING PARTNERSHIPS

The interchange of ideas and people at university-industry-government interfaces is a key to capitalizing on research. In particular, university-industry collaborations that transcend disciplinary barriers and focus on real-world problems bring many benefits, such as exposing students to the industrial environment and culture and allowing industry access to cutting-edge research. In most cases, project initiation and technology transfer decisions should be made by the private sector; the internal effort and skill of firms are the essential ingredients of innovation. The government should play a catalytic and funding role in partnerships selected for their potential to capitalize on research (Nelson, 1993, p. 510).

Many large corporations now depend heavily on external sources of research. For example, DuPont's partnership with researchers at the University of North Carolina has led to new olefin polymers that may open a multimillion-dollar business. IBM, Toshiba, and Siemens are collaborating to produce 256-megabit memory chips. Even as they compete in the marketplace, companies must remove more barriers in order to maximize R&D efforts. New understandings from universities can improve a company's ability to improve products and exploit new opportunities. To support this process, companies once relied on their own expertise; now they maintain outside partnerships for this purpose. Of course, partnerships are difficult to form and manage effectively; many fail to live up to expectations.

In a true collaboration, both partners find areas of mutual interest, benefit from synergies of ideas, and share results equitably. Benefits can include shorter development times, better products, lower risks, and lower costs. However, not all areas can benefit from partnerships, and there is a danger that some forms of collaboration between university and industry could create conflict with the basic educational purpose of the university. Harvey Brooks (1993) proposes "buffer institutions" at, but not quite of, universities that would pursue these agendas.

Many universities are struggling to align internal policies, especially those regarding intellectual property rights, with industrial partnerships. One common formula is to grant the industrial sponsor rights of first refusal to an exclusive license; partners delay royalty discussions until they actually make a patentable discovery (Council on Competitiveness, 1996).

In some fields, potential partners continue to be isolated by cultural barriers. Several participants in a workshop on piezoelectric ceramics mentioned that U.S. ability to capitalize on research in this field would be improved if students and academic researchers had a better understanding of the potential applications of their work (Freiman, 1996).

Innovative partnerships are being tried by state governments. The Minnesota Technology Partnership Fund seeks to stimulate relationships between small companies and postsecondary institutions. Its objective is technology transfer—to increase the access of small, technology-oriented companies to academic resources. A company is invited to apply jointly with an academic partner to fund R&D that is designed to lead to near-term commercialization. One rationale is that economic activity can be stimulated by state incentives and the presence of a major research university.

State governments have improved their ability to help manage programs. The U.S. Innovation Partnership, which links federal research and innovation policy making to states through the National Governors' Association, provides an important new mechanism. State governments are increasingly responsible for delivery of technology and training services and, more generally, for technology diffusion and utilization. They are also better situated than the federal government to integrate training and education in the local setting.

MAINTAINING A STRONG ENVIRONMENT FOR CAPITALIZATION

For the nation to realize returns on its investments in science and technology, a favorable environment for capitalization is necessary. The discussions in Chapters 2 and 3 illustrate the importance of a strong environment, and how it interacts with the other capitalization ingredients identified by the working group. For example, the favorable environment in the United States for commercializing technology through the formation of new firms has accelerated capitalization in areas such as the Internet, monoclonal antibodies, and other areas of biotechnology. For the most part, the U.S. antitrust environment has encouraged innovation and the free flow of information about key innovations. Without a favorable environment, realizing returns on investments in cutting-edge research and the creation of superior science and engineering human capital would take longer or would not occur.

Although the working group did not uncover any general concerns in this area that require corrective action, conditions and perceptions can change quickly. As pointed out in Chapter 3, the financing environment for new science- and technology-based firms historically has exhibited wide swings. Shifts in the investment environment can slow innovation in other ways as well. Some years ago, it was asserted that Japan-based companies enjoyed an advantage over others in pursuing long-term innovation strategies because of their ability to access low-cost, patient capital (Prestowitz, 1988). Now it is apparent that the efficiency of capital deployment is critical as well (Lahart, 1998). Although recent U.S. economic performance has been excellent, the low U.S. savings rate and short time horizons for investment could reassert themselves as U.S. weaknesses in the future (NRC, 1999).

Other aspects of the capitalization environment are changing, and will undoubtedly require adjustments and adaptations in the future. For example, the growth of new high-technology industries, particularly computing and information technology, is posing challenges to the enforcement of competition and antitrust policies. Differences in national systems for trade, investment, and industrial development still cause international frictions (Hamburg Institute for Economic Research et al., 1996). Other issues, such as product liability, have been mentioned as barriers to innovation in particular industries (Hunziker and Jones, 1994).

In short, it will not be enough for the United States to ensure a strong, diverse portfolio of science and technology investments, strengthen science and engineering human resources, and facilitate cooperation between sectors. Policy makers and the science and engineering enterprise must continue to recognize the importance of the capitalizing environment, and help to maintain and improve it.

Chapter 5

RECOMMENDATIONS

In the Goals report, COSEPUP (1993) recommended that, for the sake of the nation's well-being, the United States should be among the leaders in all major fields of science, and preeminent in selected fields of national importance. That report also described the need for an appropriate mix of short-term and long-term research: Short-term research is needed to bring us tomorrow's new products and ideas; long-term research is needed to ensure the flow of new products and ideas for the day after tomorrow.

The current report reinforces the Goals report in asserting that research leadership is prerequisite to such national objectives as economic competitiveness, public health, better education, a clean environment, and improved quality of life. It also extends that assertion, however, with the following observation: If the United States is to optimize the returns on its research investments, it must maintain effective mechanisms to capitalize on research—that is, to transform the fruits of research into national benefits.

On the whole, the United States has succeeded both in performing research at very high levels across all major fields and in capitalizing on that research for the benefit of society. U.S. researchers work at or near the forefront of most fields, where they are able to make or contribute to basic discoveries. In addition, a favorable capitalizing environment encourages the extension, application, and utilization of these discoveries and of other discoveries made abroad.

A particular U.S. strength is movement from fundamental breakthroughs to first demonstrations or product applications, as exemplified by the development of monoclonal antibodies and other biotechnology advances, as well as most of the hardware and software technologies underlying personal computers and the Internet. The belief expressed by some in the 1980s and early 1990s that other countries have nimbly leapt ahead of American companies to transform U.S. research breakthroughs into hit products is an oversimplification, according to the working group's investigation. In cases where other countries did succeed in profiting from U.S. inventions, such as semiconductor memory, flat panel displays, and VCRs, this was generally due to their ability to improve existing products or adapt them to meet the needs of new markets. As discussed in other parts of this report, making incremental improvements and creating new markets for existing technology are crucial elements of capitalization and will remain so in the future. However, from the examples examined by the working group, it appears that countries lacking a critical mass of cutting edge research in a given field are rarely able to take international science and engineering breakthroughs and proceed directly to successful commercialization.

As discussed in Chapter 4, the key elements contributing to U.S. ability to capitalize on investments in science and technology are (1) strong, stable funding for a diverse national portfolio of science and technology investments; (2) a favorable environment for capitalizing, characterized by strong incentives for innovation and free movement of ideas and people; (3) a skilled, flexible science and engineering human resource base; and (4) mechanisms for research and capitalization that support cooperation between academic, industry, and government sectors.

In some respects, these recommendations echo those found in other recent reports. COSEPUP is encouraged that this effort will contribute to a growing national consensus on key issues of science and technology policy. Although several of the tasks that COSEPUP identifies will be familiar to those regularly engaged in these issues, they remain critically important for the ability of the United States to capitalize over the long term.

Recommendation 1: The allocation of federal research funding needs to incorporate an explicit and continuing concern for capitalizing on research

Assessment

U.S. capitalization efforts have benefited from the strength and diversity of the U.S. research funding portfolio over a long period of time. Strong private and public support has allowed the United States to remain at the frontier across all fields. Diversity in terms of missions, funding sources, time horizons and performing institutions has encouraged the development of superior human resources and infrastructure that have contributed to capitalization. Changes in the government and industry funding environment that do not take these features into account may jeopardize the capitalizing process in the future.

Action Points

1. **The federal government should provide sufficient funding to sustain a strong, diverse portfolio of science and technology investments. A particular current task for the federal government is to act as "funder of last resort" of long-term science and engineering research to compensate for general pressure toward short-term research.**

The process of discovery is particularly vibrant when basic science and engineering research is conducted in proximity to applied and developmental research. Curtailment of either category reduces synergies and dilutes the intellectual climate.

Three specific concerns about trends in federal funding were raised during the workshops. First, the working group was told that universities, industry, or both need to perform more long-term research in several fields, including information networks, some areas of catalysis, computational biology, and semiconductors. In fields where commercialization is advancing rapidly, government agencies may not see the need for long-term research, and industry may have weak incentives to step in.

A second concern is that in fields such as materials science there is scant public awareness of the need for technological research and the maintenance of expensive systems on which advanced research depends (COSEPUP, 1998). Declines in basic technological research also are caused by reduced agency budgets.

A third concern is that more focused efforts are required to capitalize on research in areas of national importance where strong capitalization pathways do not exist. One possible example is the application of research on cognition and learning to education. Improving capitalization on social sciences research to address U.S. health and social needs may be a fertile area for more intensive study.

2. **The federal government, working with the science and engineering community, should continue to develop tools for monitoring and assessing the national science and technology investment portfolio. Evaluations of research funding allocations should recognize the importance of capitalization and seek to identify the long-term contributions of research to meeting national goals, both within specific fields and across the U.S. science and engineering enterprise.**

In recent years, there has been growing interest in measuring the effectiveness of government agencies and programs in achieving stated goals. One significant manifestation of this trend is the Government Performance and Results Act of 1993 (COSEPUP, 1999). Although early attempts are under way to develop meaningful metrics and tools, such as benchmarking studies, surveys, and quantitative gauges, evaluating the payoffs of long-term knowledge-driven research is inherently difficult. These tools should be sophisticated enough to assess conditions not only in research-related activities but across the spectrum of conditions that influence capitalizing, from human resources and trade policies to antitrust regulations and capital formation.

Recommendation 2: Maintain a favorable economic and regulatory environment for capitalizing on research

Assessment

One of the reasons the United States has been so effective at capitalizing on research is that it maintains a relatively favorable environment of economic conditions, regulatory laws, tax structures, and access to capital. Recently, the capitalizing climate has been especially favorable because of the availability of venture capital and other forms of private financing to launch science- and technology-based ventures.

These interlocked conditions have not always been as favorable as they are today. For example, there was virtually no contribution from venture capital financing before a sequence of regulatory actions two decades ago (see Chapter 3). The magnitude of such discrete actions may seem modest when they are achieved, but their cumulative power is great. This power can be illustrated by the great discrepancies in economic progress achieved by nations that have had essentially equal access to public scientific knowledge (Patel and Pavitt, 1994).

As a nation, we should continue to improve our understanding of how the capitalizing process works and to maintain and improve its effectiveness. In the fields that the working group has examined, there appeared to be no general, systemic barriers. Some fields appear to face specific serious capitalization challenges, such as the application of research on cognition and learning in education, which could be examined in more detail through a more focused study. Should the pace of capitalizing falter in the future, the nation will face the challenge of identifying causes and finding solutions, just as private firms learn to pinpoint problems and take corrective steps when they lose market share.[1]

Action Points

1. **Federal and state governments should ensure that individuals and institutions continue to have strong incentives to capitalize on research.**

This is especially important when research has been supported by public funds. Public policy tools include economic policies, regulations, standards, procurement, taxation, patent and copyright protection, and consistency of funding over time.

2. **Universities should continue to review and update policies that affect capitalizing on research.**

Universities play an important and growing role in the capitalizing process. In some fields, such as the life sciences, this role has been direct and prominent. Yet there is considerable disagreement over how universities can sustain and expand their contributions to capitalization in ways that do not conflict with their core educational mission. For example, some universities have allowed investigators the freedom to own equity in companies, and to share the profits of patented discoveries as sources of institutional income. Institutions may even assist faculty in

[1]Trends that would point to a faltering pace of capitalization in the United States might include (1) the emergence of large, persistent mismatches in the supply of and demand for science and engineering talent across a wide range of fields; (2) a slowdown in the growth of significant U.S. industrial activity based on U.S.-generated science and technology; and (3) increased foreign capitalization on U.S. science and technology without increased U.S. capitalization on foreign science and technology.

negotiating agreements with industry. At the same time, excessive faculty involvement in off-campus activities may weaken the institution's teaching and basic research functions. Approaches that work in one field or institution may not be appropriate in another setting.

Recommendation 3: Regard the education and training of scientists and engineers as an essential ingredient for capitalizing on research

Assessment

It goes without saying that discovering new knowledge depends on human resources—well-educated scientists and engineers. It is less apparent that those same scientists and engineers often play equally important roles in capitalizing on research—developing it, applying it, transforming it into applications of value to society. The study has shown that the ability of superior talent to move across sectoral and disciplinary boundaries has contributed greatly to U.S. ability to capitalize.

The universities that educate and train scientists and engineers thus have a double duty: to educate and train not only those who will have careers in research, but also those who will become entrepreneurs, managers, consultants, investors, or policy makers. Universities also can play a more active role in helping students to prepare for these roles. In recent reports, COSEPUP (1995, 1996b) discussed the steps that universities and faculty can take in this area and developed specific suggestions on implementation.

The apparent simultaneous shortage of skilled people in the emerging area of bioinformatics and the glut of new Ph.D.s in the life sciences is one example of a current mismatch. Universities, working with the federal government and industry, need to develop ways of responding to emerging human resource needs while maintaining their traditional strengths.

Action Points

1. **Universities, cooperating with science and engineering societies, government, and industry, should develop better mechanisms to recognize signals of manpower shortages or gluts, and communicate this information to students.**

Such signals include the simultaneous underutilization of well-trained people in established fields and shortages of well-trained people in emerging fields. Students, especially early in their careers, need current information and projections to make wise choices about the course work and other learning experiences they require. In the past, efforts to predict supply and demand of scientists and engineers have not been very successful. Mismatches between supply and demand in science and engineering labor markets cannot be eliminated, but it should be possible to reduce them.

2. **Enhance diversity in funding mechanisms for advanced science and engineering education, and develop ways to measure the effects of alternative approaches.**

To a large extent, a student's activities are determined by the kind of support received. Research assistantships support students by employing them to work in the research program of the advisor. Although many students benefit from this close association with a single advisor, others would benefit from more autonomy in choosing courses, research projects, and perhaps off-campus internships. Federal agencies should continue recent efforts to adjust their funding mechanisms to encourage more innovative approaches to advanced science and engineering education in universities.

3. **Industry, universities, and government must recognize the importance of lifelong learning for the nation's science and engineering human resources.**

Recommendation 4: Build stronger partnerships between academia, industry, and government

Assessment

As more businesses turn to partnerships to supply new techniques and knowledge (see Chapter 3), the transfer of technology needs to be as seamless as possible. A major strength of U.S. research and capitalization on that research has been the flow of people and ideas between universities, industries, and government.

Nearly all of the successful examples of capitalization examined by the working group have depended on the collaboration of scientists and engineers who have diverse perspectives, time frames, and talents, and who represent the whole web of public, private, and educational institutions. This web has become far more complex in recent years, as many large corporations reach outside the firm to rely on universities, suppliers, and subcontractors as sources of research. Similarly, technology-oriented start-ups that are too small to support basic research programs often depend on close contacts with university researchers.

Yet, it is necessary to have realistic expectations about partnerships. For example, government-industry partnerships cannot be expected to substitute for either the government's responsibility to serve as funder of last resort across all major fields or the responsibility of individual companies to make the research investments that will enhance shareholder value over the long term. Nevertheless, experiments with partnerships over the past 10 years have yielded positive examples and lessons.

Action Points

1. **Governments, industries, and universities should continue to experiment with partnerships and consortia, work to lower barriers,**

and evaluate programs so that lessons can be incorporated into future collaboration.

The overarching goals of partnerships should be to conduct mutually beneficial research, invigorate education, and capitalize on research for the benefit of society. Partnerships should focus on precompetitive work, leaving product development to the private sector. Industry should share costs and take the initiative in research directions. Examples to be emulated include the Semiconductor Research Corporation and the Data Storage Systems Center [see discussion in Chapter 2].

2. **State and federal governments can help to arrange new partnerships.**

Now that the role of the federal government as guaranteed purchaser has diminished, it has the opportunity to create a new role as facilitator, funder, collaborator, and information resource for both industry and academia. It can make long-term investments in a "knowledge-based infrastructure"—the capacity of the entire system of private entrepreneurship, human resources, investment, and advancing frontiers of technical knowledge. State governments increasingly are able to deliver technology and training services (e.g., through community and technical colleges) and, more generally, to assist in technology diffusion and utilization. Through local networks, they often can play an effective role in integrating training and education.

APPENDIXES

Appendix A

EXAMPLES OF CAPITALIZATION IN FIELDS OF RESEARCH AND APPLICATION

To gain a better understanding of the capitalization process, the working group examined a number of specific fields of research and application during the course of the study. In several of these cases, a workshop or expert panel discussion was organized and a write-up was prepared on the basis of discussion and background research. The experts who participated in the discussion and others were asked to review the draft write-ups for accuracy. In other cases, the working group prepared write-ups based on telephone interviews with experts and a survey of the relevant literature. The working group has worked to ensure that the write-ups give an accurate picture of a given field, but they inevitably reflect the insights and opinions of the individual experts consulted. In several cases, the working group worked closely with other Academy complex units in organizing the workshops and preparing the write-ups.

The working group was only able to cover a limited number of fields and did not attempt a comprehensive assessment of capitalization across all fields in every country. Through experimentation, the working group found that the examination of well-defined subfields and specific applications (e.g., speech recognition and monoclonal antibodies) generated more useful insights than the study of broader fields (e.g., computer science and biology). The examples were selected through consultation among working group and COSEPUP members, staff, and other experts.

The working group looked for examples in which success and failure, and the causes of each, could be determined clearly. This proved to be difficult. In most of the examples, a closer examination showed elements of both success and failure. In some instances the success factors and barriers to capitalization were fairly clear; in others, causality was difficult to establish.

The examples illustrate a number of important issues related to capitalizing, and are referenced throughout the report. The examples, along with the existing literature that the working group reviewed on topics such as innovation and technology transfer, provided the raw material for the framework of the study, the conclusions, and recommendations. Write-ups of the examples are provided in this appendix and in Box 3-1. Table A-1 summarizes the examples and insights.

Table A-1 Capitalization in Specific Fields Examined During the Study

Field [Source of information]	*U.S. Standing in Research*	*Capitalization Situation and Trends*	*Key Points for the Study*
Catalysis [workshop, background research]	• The United States is performing at the frontier. • U.S. universities have become world leaders in a number of subfields over the past 15 years. • Integration of research and education is seen as a U.S. advantage. • U.S. petrochemical companies have cut back on research in some areas. • Excellent academic and industrial research in Europe.	• The chemical industry has long been characterized by intense global competition. Companies in the United States, Europe, and Japan are effective at capitalizing on research wherever it appears. • New opportunities are emerging to apply catalysis in advanced materials and more environmentally benign processes. • Some experts are concerned that, despite a growing commonality of interests, U.S. academia and industry appear to find it easier to work with foreign partners than with each other in these promising areas.	• It appears that in this field U.S. industry is cutting back on long-term work. • Confirms the value of working at the frontier in a global industry. • Industry-university differences in perspective emerged over how to promote effective collaboration. • Several discussants highlighted the excellence in U.S. advanced education, but raised questions over whether students understand industry problems. • Government plays a smaller role in this field relative to others examined in the report. • Start-up companies play a smaller role in this field than in several others examined.

Table A-1 Continued

Field [Source of information]	*U.S. Standing in Research*	*Capitalization Situation and Trends*	*Key Points for the Study*
Application of research on cognition and learning to education [interviews, literature survey]	• The United States appears to be working at the frontier. • National Science Foundation, U.S. Department of Education, National Institutes of Health, and private foundations support relevant research. • A number of experts consulted believe that research has produced insights that could be applied successfully in classrooms.	• It is inherently difficult to translate research findings into real curricula and teaching practices, and to test new approaches. • Some work aimed at capitalization in this area is going on, but the scale of effort is not large. • Capitalizing requires cooperation between researchers, education schools, teachers, and school districts, but incentives to collaborate are weak. • It is well known that other countries outperform the United States in K-12, but it is unclear whether any of this gap is due to more effective capitalization abroad.	• Unlike some of the other examples, there are few examples of success, and few established capitalization pathways. • The policy environment for capitalization is not particularly supportive, and the research community itself is somewhat fragmented.

Continued

Table A-1 Continued

Field [Source of information]	*U.S. Standing in Research*	*Capitalization Situation and Trends*	*Key Points for the Study*
Bioinformatics [workshop, commissioned paper]	• The United States appears to be at the frontier in this rapidly emerging field. International companies are ramping up research activities in the United States. • At the same time that many Ph.D. holders in the life sciences appear to be underemployed, there is a shortage of people combining experimental expertise and computer skills. This may emerge as a barrier to both long-term progress in research and capitalization.	• The data produced by the Human Genome Project and related efforts is proving valuable to pharmaceutical research much more rapidly than anticipated. • Utilization of engineering approaches to the study of relationships between gene expression and disease promises to deliver many new therapies. • U.S. mobility between academia and industry is an advantage in capitalization, but we may be eating our academic seed corn.	• Although the U.S. appears to be doing as well or better than other countries, this example raises serious future questions about how we invest in human capital. • The life sciences are more insulated from nonacademic labor market demand than most other fields. • It has been difficult so far to establish new interdisciplinary programs in this field.
Liquid crystal displays [interviews, background research]	• The original discovery of liquid crystals was made in Austria in the 19th century. • Key developments in liquid crystal materials were made in England in the 1960s. • The first prototype LCD was developed at RCA's Sarnoff Lab in the United States.	• Widespread applications of LCDs emerged in the calculator and watch businesses in the 1970s, with Japanese and U.S. firms both involved. • Today, the largest market for LCDs is in portable computers. • Japanese firms emerged as leaders in the 1980s because of focus on incremental improvements, cost, and manufacturability. • Korean firms have entered the LCD business.	• Even in this area, where other countries have taken the subsequent lead in commercialization, the United States was first in reducing fundamental understanding to practice. • Illustrates Japanese strengths in improving technologies developed abroad and creating new applications.

Table A-1 Continued

Field [Source of information]	*U.S. Standing in Research*	*Capitalization Situation and Trends*	*Key Points for the Study*
Monoclonal antibodies [workshop, background research]	• The fundamental breakthrough by Köhler and Milstein was made in Britain. • The United States has produced many of the subsequent research gains.	• Development of human diagnostics and therapeutics has been pioneered by U.S. start-ups. • There were capitalization setbacks in the early 1990s, when several septic shock therapies were not successful. • More recently, several therapies have proven successful. Monoclonal antibodies remain an important area in the biotechnology industry.	• Illustrates the importance of working at the frontier to capitalize on foreign science. • Illustrates the importance of venture capital, university-industry collaboration, and the scientist-entrepreneur as important U.S. strengths.
Network systems [workshop]	• The United States appears to enjoy clear leadership in many areas. • Government investment in the Internet and related areas has played a major role. • Applications and commercialization are moving so rapidly that it is difficult to interest talented people in more fundamental areas of research. • Ironically, government investment in fundamental research is seen to be lagging, partly because of the rapid growth in market success for U.S. companies. • A number of the prominent U.S. companies do not do research, just product development.	• Taking into account all areas of networking, this is an enormous, growing market. • U.S.-based companies are the leaders in capitalization.	• Illustrates the serendipitous spin-off benefits of government mission-related investments. • Illustrates the importance of venture capital and engineer-entrepreneurs as U.S. strengths. • Illustrates the possible problems of imbalance between long-term and short-term research investments. • Illustrates the shortening time horizons of U.S. industry.

Continued

Table A-1 Continued

Field [Source of information]	*U.S. Standing in Research*	*Capitalization Situation and Trends*	*Key Points for the Study*
Numerical-control machine tools [background research]	• The original breakthrough was made at MIT on an Air Force contract.	• While capitalization in the United States focused on higher-end defense applications, Japanese companies developed lower-cost applications of NC technology in general-purpose tools.	• Illustrates the effectiveness of Japanese institutions that acquire, diffuse, and improve technology, such as industry associations. • Illustrates challenges to the United States to capitalize in fields requiring incremental improvement over the long term.
Optical sensing [workshop]	• The focus of the discussion was on fiber optic sensors. This is an interdisciplinary and somewhat fragmented field, where applied work is targeted at particular needs. • The United States is clearly ahead in areas where there is significant funding, such as space and health care applications. The United States also publishes more papers. One expert believed that Europe might be ahead overall, however.	• Optical sensors have a number of advantages for specific applications, but have not emerged in a large commercial market. • In some areas it has been difficult to reach cost-performance levels necessary to displace older technologies in established applications. • Both small and large companies play important roles.	• Participants credited the SBIR program with making important contributions to capitalization efforts by smaller U.S. companies. • Concern was expressed that U.S. government funding is becoming too focused on applications work with short time horizons. • Participants expressed the view that greater familiarity by students with industry needs would enhance U.S. ability to capitalize.

Table A-1 Continued

Field [Source of information]	*U.S. Standing in Research*	*Capitalization Situation and Trends*	*Key Points for the Study*
Oxygen steelmaking [background research]	• The process was developed in Austria, but was widely available worldwide through licensing.	• Capitalization on this technology was an important factor in Japan's emergence as a leader in the global steel industry during the 1960s and 1970s. • The Japanese government coordinated licensing of the technology, and encouraged collaboration in developing generic technology. Firms competed in implementation. • U.S. companies did not capitalize as effectively, and fell seriously behind in the steel industry.	• Illustrates the Japanese government's role in facilitating foreign technology acquisition during the high-growth period.
Piezoelectric ceramics [workshop]	• Most groundbreaking work has been done in the United States, funded by the DoD and performed at U.S. universities. • Japanese companies that manufacture ultrasonic imaging machines are also supporting long-term work.	• Applications are in actuation and sensing in a number of areas. • U.S. companies lead in the military and mission-critical applications supported by government funding (Hubble Telescope). • Commercial applications in large markets are emerging, such as in hard disk drive manufacturing. Japanese companies appear better positioned to capitalize.	• Illustrates that U.S. advantages in venture capital, flexible human resources, and strong government research support do not translate into capitalization success in all fields. In fields with low margins, a significant existing infrastructure, and a need for incremental improvement, Japanese companies are still formidable.

Continued

Table A-1 Continued

Field [Source of information]	*U.S. Standing in Research*	*Capitalization Situation and Trends*	*Key Points for the Study*
Speech recognition [workshop]	• Speech recognition has been a focus of long-term government and industry research support since the 1960s. • The United States is working at the frontier, and has more extensive activity. Europe and Japan also have well-funded programs.	• Despite progress in fundamental research over many years, speech recognition did not find its way into applications until the 1980s. • Capitalization appears to be accelerating, and occurring fastest in the United States. • The increased power and lower cost of computer hardware and other external factors contributed to capitalization.	• Large U.S. companies are more focused on results and products than previously. In this field the shift has produced benefits. • As in other rapidly growing fields in information technology, there is a problem of retaining some of the best talent in academia. • Illustrates that long-term efforts, a combination of progress in a range of fields, and a period of "research gestation" may be required for capitalization to occur
Fuzzy logic [interviews, background research]	• The United States produced the first breakthrough. Research communities in Europe and Japan embraced this work, and now excellent research is ongoing around the world. • A substantial group in the U.S. research and applications community believes that the benefits claimed for fuzzy logic are easier to come by using traditional logic.	• First applied by European and Japanese companies in industrial controls, transportation systems, and home appliances. • Slowly being applied by global U.S.-based companies.	• A rare example of a U.S. research advance first reduced to practice and commercialized abroad.
Applications of economics: options pricing and spectrum auctions [interviews, background research]	• U.S. academic economists produced the relevant breakthroughs.	• Research in both fields was first utilized in the United States. • Economics research does have established pathways for capitalization by financial services firms and policy makers.	• Economics research is not a top priority of national policy, but the field has generated a number of advances that have been capitalized on over the years.

MONOCLONAL ANTIBODIES

Antibodies are soluble proteins produced by the immune system in response to potentially harmful antigens such as viruses and bacteria (Haber, 1996). They bind to specific antigens and help to destroy them. Antibodies to even a single antigen are highly diverse and heterogeneous, produced by many different types of cells. Some antibodies, once activated by a disease, help to provide continuing resistance to that disease. This characteristic makes it possible to develop vaccines, which consist of killed or weakened bacteria or viruses that stimulate the production of antibodies against those antigens (Biotechnology Industry Organization, 1989).

For many years, scientists tried to produce antibodies in pure form. As part of their research on the genetic basis of antibody diversity, Georges Köhler and Cesar Milstein developed a method of producing large amounts of pure, monoclonal antibodies (MAb), in 1975 (Raiten and Berman, 1993). In this method, tumor cells that reproduce endlessly are combined through cell fusion with mammalian cells that produce an antibody. The resulting line of fused cells, or hybridoma, are immortalized and produce only one type of antibody. Köhler and Milstein won the Nobel Prize in 1984 for this work.

The discovery of MAb technology has been a boon to research and public health, although at various times, expectations have been higher than what could be delivered in the short term. MAb/hybridoma research and applications, both past history and current trends, illustrate a number of the strengths and issues for the United States and its ability to capitalize on research leadership, particularly in biotechnology and biomedical fields.

Initial applications and commercialization

Although Köhler and Milstein had done their work in Great Britain, the strong U.S. research base in immunology was quickly able to understand the implications of the discovery and begin developing applications. Much of this work was done in universities and was funded by the National Institutes of Health (NIH) and other government agencies. Close collaboration between small high-technology start-up companies and universities characterizes commercial biotechnology in the United States. The U.S. environment for research and commercialization also allowed for relatively free movement of skilled researchers from universities to industry, and for the recruitment of experienced managers for start-up operations.

One prominent example of the importance of university-industry collaboration and "people linkages" is Centocor, Inc., and its founder, Hubert J. P. Schoemaker. Schoemaker immigrated from the Netherlands and received a Ph.D. in biochemistry from Massachusetts Institute of Technology (MIT). He then went to work for the medical products group at Corning Glass Works (now Corning, Inc.), which was using polyclonal antibodies for diagnostic applications (H. J. P. Schoemaker, Centocor, personal communication, November 1996). Schoemaker's scientific and business background provided good preparation for launching a company to commercialize MAb research done at universities. Centocor also was able to attract seasoned managers from other health care companies.

Since polyclonal antibodies already were being used for diagnostics, utilizing MAb as a superior technology for in vitro diagnostics was fairly obvious, and was the first commercial application of the technology. Relative to polyclonal antibodies, tests utilizing MAb are more accurate and cost-effective. By introducing the antibody with a radioactive or chemical "tag" into a blood sample, the amount of antigen can be measured according to how much antibody binds with the antigen. Regulatory approval of in vitro diagnostic products is not as long or as costly as human therapeutics and in vivo diagnostics, and so, products appeared quickly.

MAb technology is still widely used in diagnostics.[1] In addition to Centocor, which initially focused on cancer diagnostics, several other companies such as Hybritech and Genetic Systems were formed around the same time and commenced work in this area. Current diagnostic uses of MAb besides cancer are in blood typing, diagnosis of AIDS, transplantation technology, pregnancy testing, and screening for influenza, measles, malaria, herpes, and toxoplasmosis. Taken together, these applications of MAb have made a significant contribution to public health. The ability to ensure the safety of the blood supply in the wake of the appearance of HIV is one outstanding example (Raiten and Berman, 1993).

Therapeutic applications

Therapeutic applications of antibodies have been pursued for over a century. In 1895, Hericourt and Richet described the first trials in which cancer cells were injected into animals to raise antiserum for treating cancer patients (Cambridge University Molecular Biology, 1996). Although several patients showed promising results through treatment with tailored antiserum, repeated trials during the early 1900s led to results that were inconsistent and contradictory, and this line of research was dropped.

With the development of MAb technology, hopes were raised that "magic bullet" therapies for a number of diseases would be near at hand. Therapeutic development thus far has focused on treatment of tumors, neutralization of toxins and drugs in overdose, receptor blockade, inhibition of hormones or cytokines, and immunosuppression (Haber, 1996).

Development of therapeutic agents presents several additional challenges not present in the development of diagnostics. New drugs must go through several phases of clinical trials designed to establish their safety and efficacy before they can be approved by the Food and Drug Administration. Further, therapeutic applications of MAb require far greater amounts of antibody than diagnostic applications. These development and manufacturing challenges require a longer time horizon and higher levels of investment than diagnostics development. On the other hand, the potential market for therapeutics is far larger than that for diagnostics.

[1]Besides therapeutics, discussed in the next section, work has been done to apply MAb technology to in vivo imaging, but the advantages over alternative technologies have not been compelling.

Private equity, mainly in the form of venture capital, has played a key role in the financing of companies developing MAb therapeutics and other biotechnology products. Of the 1,500 U.S. biotechnology firms that existed in 1996, about 450 were venture backed, and these firms represent over 85 percent of the patents awarded, scientific research published, and drugs approved (Lerner, 1996). Although venture capital accounted for less than 20 percent of the $37 billion in external financing raised by biotechnology firms over the 1978–1995 period, venture-backed firms have raised 90 percent of the total. Venture investments have served a screening and validating function that facilitates access to other sources of funding.

Biotechnology poses particular problems for venture investors because of uncertainties and risks related to evaluating the underlying science, intellectual property risks from patent positions and the inability to use trade secrets in most cases, and business risks hinging on the management abilities of entrepreneurs (Lerner, 1996).

Still, biotechnology has been an attractive area for venture investment. Perhaps one reason is the potential market for biotechnology products, particularly therapeutics that attack serious diseases. Several companies developed MAb therapies to treat septic shock during the late 1980s and early 1990s, raising sufficient funding through venture capital, public offerings, and other mechanisms to support the costs of development. Septic shock sometimes occurs as a postoperative complication and often is fatal. Ultimately, none of these drugs gained approval in the United States.

Future prospects and issues

Work has continued on MAb therapeutics in recent years, with some notable successes. For example, the Centocor-developed ReoPro® (abciximab) reduces acute ischemic cardiac complications in patients undergoing or about to undergo angioplasty procedures, and has been on the market for several years.

As for the future, perhaps the most interesting developments are in the cancer area (R. Levy, Stanford University, personal communication, October 1996). One of the first experimental applications of MAb therapy was the development of an antibody specific to the B-cell lymphoma receptor in the tumor of a particular patient in 1981 by Ronald Levy. The antibody effectively attacked the tumor, and the patient is free of disease today. Further research showed that this customized approach produces similarly good results about 10 percent of the time, and established the principle of monoclonal antibody therapeutics. However, scaling up and refining the process of locating the antibody and producing it in sufficient quantities, and gaining FDA approval, has not been judged to be a promising enough business opportunity to attract significant investment.

Several MAb cancer therapies are already on the market or in later stage development, including a treatment for non-Hodgkin's lymphoma developed by IDEC, a San Diego-based company, and a treatment for postoperative colorectal cancer developed by Centocor. Other companies, such as Coulter, are active in developing MAb cancer therapeutics.

Research on future therapies is proceeding along several lines. For example, some work is focused on the development of immunotoxins or antibodies hooked up to toxins to attack cancer. The antibodies guide the toxin to the tumors and lymphomas. Anecdotal results of trials thus far are positive. Also, work is also being done on linking antibodies to radioactive substances to treat leukemia and other cancers.

Despite the promise of current research, it has been difficult to raise financial support for the development of cancer therapeutics based on MAb, particularly for start-up companies. Although cancer treatment is a very large market, proving efficacy, refining the manufacturing process, and gaining approval can be a long and expensive process. New MAb treatments can be more expensive to test than traditional chemical and radiation therapies. Most of the investment in this area is coming from large pharmaceutical companies and more established biotechnology firms.

Conclusion and summary

The monoclonal antibodies case illustrates (1) the value to the United States of being among the leaders in all fields of science because this position allowed U.S. universities and companies to capitalize quickly on a major breakthrough abroad, to the benefit of U.S. public health and the economy; (2) the advantages of U.S. approaches to advanced education and training that attract talented scientists from abroad and allow for the accumulation of diverse experience through movement between universities and companies; and (3) the positive impact of financial and intellectual property practices that allow university-based research advances to be commercialized. The case also raises possible challenges, such as whether investment decisions reflect an adequate or current understanding of scientific developments.

SPEECH RECOGNITION

The development of computers that can recognize human speech has been pursued in the United States by the computer science research community, computer and telecommunications companies, and government funding agencies since the 1960s. Speech recognition would hold obvious advantages over keyboards and other input mechanisms in advanced applications of information technology, and persistent efforts have gone into research over many years. Real-world products reached the market during the 1980s, and applications are expanding rapidly. Speech recognition is a good illustration of more general shifts that are occurring in the U.S. research and development (R&D) system. It also shows how capitalizing on research in a particular area may depend on research developments in other areas, as well as factors outside of research, such as the market environment.

Research

Current speech recognition systems have three major components (Figure A-1). The first task is feature extraction, which involves digitizing the sounds of speech

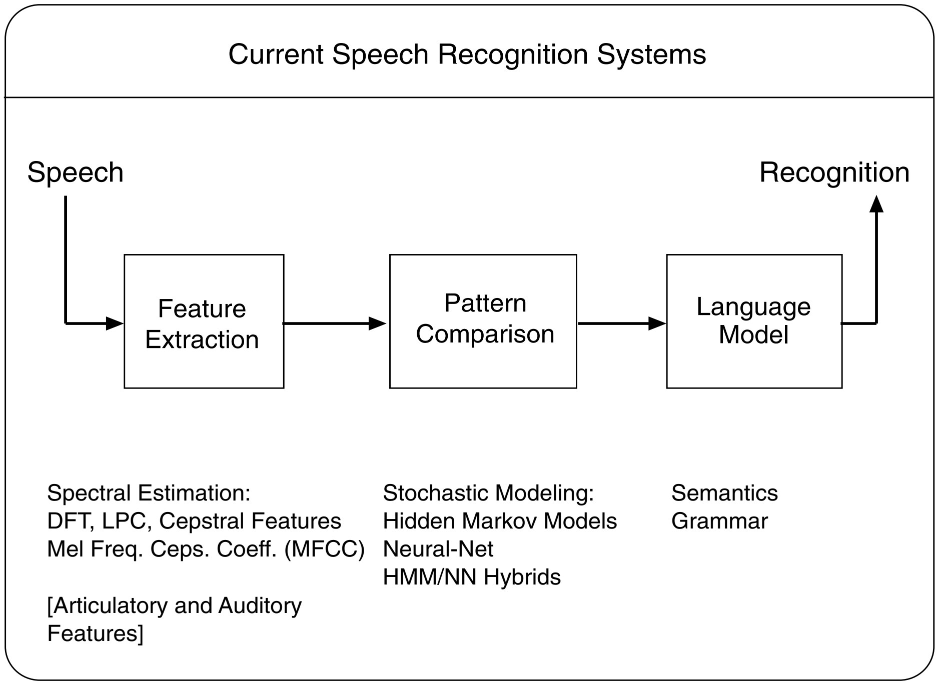

Figure A-1.
Source: Abeer Alwan.

and extracting the energy and frequency data. The second step is pattern comparison, in which digitized speech is compared with a vocabulary stored in memory. Most systems now use models of phonemes (often context-dependent models are used), the smallest identifiable sounds in a language, rather than complete words.[2] Speech patterns are compared with the models using a statistical technique called hidden Markov modeling, which calculates the probability that a sequence of such stored models, which form a word according to a task dictionary (or lexicon), matches the spoken word. The final step is the application of a language model to enforce basic rules of grammar and syntax on the recognized output sentence. The system selects the word sequence (or sentence) with the highest probability that is consistent with the task language model.

AT&T Labs, Bell Laboratories, IBM, and other industrial labs have conducted research on speech recognition for many years. Basic research on speech recognition, along with artificial intelligence and other advanced information technologies, has received government support by the intelligence community and by Department of Defense (DoD) through the Defense Advanced Research Projects Agency (DARPA), the Institute for Defense Analysis, MIT Lincoln Laboratory, and other intramural and extramural mechanisms. DARPA traditionally has provided support for research on large-vocabulary speech recognition tasks with

[2]For example, there are 44 phonemes in English. See Koprowski (1996).

potential military applications. A recent focus has been interdisciplinary approaches integrating language models and human-computer interface issues (Alwan, 1996). In recent years, the National Science Foundation (NSF) also has emerged as a significant supporter of basic research in speech recognition, and provides funding at about one-tenth the level of DARPA. One of NSF's current focuses is human-centered systems, or speech recognition applications in areas such as educational technology.

DARPA funding has produced several major advances in speech recognition research, such as advanced search architectures, integrated systems, and speaker independent systems (Cohen, 1996). U.S. government support has served to train researchers, has balanced knowledge sharing and competition, and drives a great deal of useful research. Experts consulted by COSEPUP generally rated the United States as at least among the leaders in speech recognition research. European and Japanese efforts are well funded and evaluated quite highly.

However, the strength of U.S. research efforts, by themselves, was not sufficient to produce practical commercial systems. A number of difficulties encountered in applying speech recognition in real-life situations have acted as barriers to widespread utilization. For example, it is difficult for systems to recognize continuous speech, and to reliably recognize words spoken with different accents and pronunciations or spoken in noisy backgrounds. Providing systems with enough robustness to handle realistic speech has not been a focus of basic research efforts. Although system benchmarking efforts have been a useful tool for the research community, lab systems that have performed well on benchmarking tests have not achieved the same performance in the field (Cohen, 1996).

Other enabling factors

Several developments external to research have spurred the emergence of practical commercial speech recognition systems in recent years. One important factor has been the continuous cost and performance improvement in computer hardware over the past decade, particularly more powerful microprocessors and cheaper memory. Greater processing power allows the components of the speech recognition system to work more quickly, especially given the fact that the speech and language models are both computationally- and memory-intensive. It is now possible for speech recognition systems to work in real time on modern-day personal computers (PCs). Current PC-based speech recognition systems are accurate and cost-effective enough to be widely used in several specialized markets, such as transcription of medical or legal reports, and as the primary input mechanism for PCs used by the physically challenged.

A second factor has been the emergence of market pressures and opportunities that have provided impetus for commercial systems. One important example is in telecommunications applications (Rabiner, 1996). With the breakup of the Bell System in the early 1980s and the resulting intense competition in the U.S. long-distance market, telephone companies have a strong incentive to automate calling and customer service functions to the extent possible. Telephone companies now are relying on speech recognition systems with small vocabularies that are very robust in their ability to recognize speech from speakers with a large range of accents and pronunciations. As pointed out above, AT&T Labs has been a leader in speech recognition research for many years. In recent years, heightened competition has resulted in an imperative to focus research on areas that can contribute to near- or medium-term product development.

Both of these trends are not unique to speech recognition and can be seen in other areas of information technology research and applications. Early in the development of computer science and the computer industry, the U.S. government, particularly DoD, played a key role in funding advanced research and education, and as the lead customer for new information technology applications (Langlois and Mowery, 1996). Particularly with the development and diffusion of the PC over the past decade and a half, the globally competitive commercial market has replaced DoD as the predominant driver of information technologies, even though government retains a critical role as a supporter of research. These trends also have affected large corporate central R&D facilities such as AT&T Labs and IBM. Speech recognition, which is making the transition from primarily a research field to a critical technology for a variety of future information technology products, provides an excellent illustration of more general shifts in the U.S. environment for capitalizing on research.

Future issues and challenges

A number of established companies and start-ups in the United States, Europe, and Japan are pursuing future applications of speech recognition and speech understanding technology. For example, refining and extending approaches used today in telecommunications will result in enhanced ability to automate purchases and reservations made by telephone. Additional telecommunications applications, such as voice dialing, voice access to messages, and even intelligent voice-controlled assistants—agents that can screen incoming calls—are also under development.

In PC-oriented applications, widespread utilization of speech recognition as a substitute for the keyboard and mouse is probably still some years away, at least in English-speaking countries. Computer companies are seeking to utilize speech recognition as a means to expand the PC market in China, where using keyboards is quite difficult. Because of the linguistic significance of tones in the spoken language, Chinese is perhaps more amenable to speech recognition than English.

The experts who shared their views with COSEPUP agreed on several important future trends and challenges for the United States in capitalizing on speech recognition research. First, it will be important to continue to sufficiently fund advanced research and education and to continue to pursue interdisciplinary research approaches. Basic research advances and the accumulation of generic knowledge can have a major impact on the performance of future commercial speech recognition systems. For example, a better understanding of speech production and perception, including how to model these processes, is an important target (Alwan, 1996).

At the same time, although academic researchers should not shift their efforts toward the development of products, it is necessary for researchers and students to increase their awareness of the limitations imposed by real-world conditions. The utilization of additional benchmarks to supplement the current approach, which relies heavily on word recognition accuracy, is one possible approach.

Maintaining and expanding education and training efforts also will be critical to U.S. capabilities to capitalize, since many younger academic researchers are being hired away by industry because of the expanding commercial market for speech recognition systems.

PIEZOELECTRIC CERAMICS

The term *piezoelectric* describes materials that change shape when exposed to an electric charge, and emit a charge when exposed to a physical stress (Cross, 1996). Study of piezoelectric materials makes up one part of the broader examination of *ferroelectric* substances, materials whose spontaneous electric polarization is reversible by an electric field. There are two types of piezoelectric materials: single-crystal materials and polycrystalline ceramics. The focus of this discussion is on piezoelectric ceramics and ceramic composites. Ceramics are much more complicated than single-crystal piezoelectric materials, and are promising for a range of applications because of a greater ability to engineer their properties as opposed to those of single crystals. The ceramic material that is the subject of most of the experimental work and applications in this area is lead zirconate/lead titanate (PZT).

The primary applications of piezoelectric materials are sensing and actuation. Piezoelectric ceramics have several advantages over alternative mechanisms such as traditional mechanical systems (electromagnetic, hydraulic, pneumatic), resistive/capacitative strain gauges, and optical fiber. First, because piezoelectric materials allow direct conversion between mechanical and electrical energy, no translation equipment or external power sources are necessary. Also, because PZT is highly sensitive, devices can be made very small. Further, empirical work on additives to PZT has yielded materials with modified "hard" or "soft" responses, although the theoretical explanation for how these additives work has not been established completely.

However, sensing and actuation systems using piezoelectric ceramics have some disadvantages. For example, the piezoelectric "working point" may drift with time, and it is difficult to make the materials completely stable. In addition, sensing and actuation systems using piezoelectric ceramics are subject to electromagnetic interference, possible ground-loop problems, and temperature limits.

When PZT is used in a polymer composite, complementary dielectric and elastic properties can be designed. The key elements in designing a composite are connectivity (the mode in which the phases interconnect), symmetry of the arrangement, and scale. The desired scale of the composite arrangement depends upon the wavelength of excitation.

Research motivation and leadership

Most of the groundbreaking research on piezoelectric ceramics and applications has been done in the United States. Most of this work has been funded by DoD and performed at universities. The U.S. Navy and the Office of Naval Research (ONR) have had a particular interest in developing piezoelectric materials. For example, the use of piezoelectric active mounts could contribute to submarine stealthiness by canceling mechanical vibration (NRC, 1997b). Microactuators and microsensors utilizing piezoelectric ceramics also could serve other defense-related functions, such as in "smart structures" that would reduce turbulence on airplane wings. Applications of piezoelectric ceramic sensors also have been developed in the medical field, most prominently in ultrasonic imaging.

Although excellent research is being done outside the United States, particularly by Japanese companies that manufacture ultrasonic imaging machines, the United States is still the clear leader in research in most areas and is among the leaders in a few others. One of the emerging areas of major research interest is films for micro (or mini) electromechanical systems (MEMS).[3] Piezoelectric ceramics have distinct advantages because of the ability to make effective devices that are very small. Possible MEMS applications that would utilize piezoelectric ceramic components include minipumps to allow chemistry or DNA sequencing on a chip, microreactors, microinstruments such as tunneling devices and mass spectrometers on a chip, and microrobots for remote medical diagnostics and minimally invasive surgery.

In addition to leadership in research, the United States also leads in the applications of piezoelectric ceramics that have motivated government research funding. In addition to the naval and other military applications discussed earlier, these include other mission-critical applications such as actuators for space mirrors, including those utilized in the Hubble Space Telescope. The Hubble Telescope utilizes deformable optics, or mirrors that are bent by very small amounts of strain, and need to be tuned in service. Piezoelectric ceramic actuators can provide the small amounts of force required for this type of tuning.

What all of these mission-critical applications have in common is that the specific property of the device is valued more highly than cost (these are expensive, one-of-a-kind or low-production-run systems) and reliability (it is possible to rigorously test all components). These applications also do not have a great deal of economic impact. The United States has a strong research base in advanced materials but there is no advanced materials industry as such. In the emerging high-volume, industrial, and consumer applications of piezoelectric ceramics, Japan and perhaps other countries have advantages relative to those of the United States that may allow them to capitalize more quickly and effectively.

[3]Some experts believe that most of the emerging applications will be in minisystems or those in the micron to millimeter scale, rather than the submicron world (Cross, 1996).

Hard disk drive applications: Challenge to U.S. ability to capitalize

Discussion at the COSEPUP workshop focused on the application of piezoelectric ceramics in manufacturing hard disk drives (HDDs) as an example of the challenges facing the U.S. system in capitalizing (Cima, 1996). The HDD industry is growing very rapidly along with the PC market and was expected to be a $23 billion industry in 1998. Many of the leading companies are based in the United States, such as Seagate, but do a significant amount of their manufacturing overseas.

The HDD is a complicated mechanical device. At its heart is the slider, a block of ceramic material on which a sensor is mounted, which skims over the surface of the disk and helps regulate the position of the read/write heads. Over 300 million heads are made per year. Manufacturing the sliders involves a combination of ultraprecision machining and very large-scale integration. They are made from a titanium carbide-aluminum oxide composite, which comes to the manufacturer in the form of a wafer. On the surface are recording devices made of magneto-resistive thin film. The sliders are built on the wafer, and diced out.

As the market and capacity of HDDs have grown, cost and the tolerance levels of components have shrunken. The slider that faces the head needs to be manufactured to a tolerance of 150 Å and to cost less than a T-shirt. This is done through a process known as mechanical lapping. Resistant film is applied to the wafer to keep track of size, and is actively sensed during the lapping process. As differences in height along the surface of the wafer are detected, stacks of actuators adjust the shape of the polishing arm and the rate of polishing accordingly. These stack actuators use either piezoelectric ceramics or an older technology known as voice coil.

Manufacturing the stack actuators used in mechanical lapping equipment is still a fairly low volume business. The products are sold to the disk-drive makers themselves (some of whom manufacture their own equipment) or independent equipment vendors. However, this is a very important enabling technology for the HDD and PC industries. Also, as the price of actuators drops and precision improves, there is a possibility that piezoelectric devices will replace voice-coil mechanisms in the HDD itself. The small piezoelectric displacement would need to be amplified. If this comes about, it would be a significant commercial application, with anticipated volumes of a billion or more devices per year in the early part of the next decade.

AVX Corporation is based in Myrtle Beach, South Carolina, and is majority-owned by Kyocera, a leading Japanese ceramics company (Rawal, 1996). AVX's main line of business is the manufacture of multilayer ceramic capacitors used in a variety of electronics applications. The AVX Myrtle Beach plant employs 2,400 workers and produces over 100 million components per day.

Several years ago, spurred by a subcontract from Lockheed Martin related to space mirrors, AVX began developing and manufacturing piezoelectric ceramic stack actuators. Besides HDD applications, AVX is trying to develop other markets for the technology. Although AVX has captured a significant share of the HDD manufacturing equipment market and there is potential for higher-volume business if stack actuators are introduced in the HDD itself, this line of business still is not large enough to be a consistent moneymaker.

Although majority-owned by a Japanese corporation, AVX operates according to U.S. investment and business criteria. It is very difficult for AVX or other U.S.-based companies to stay in businesses with marginal near-term prospects, regardless of the size or profitability of future markets. By contrast, AVX's competitors, such as Japan's Murata and TDK, are able to operate on a longer time horizon.

The structure of the microelectronics business plays a part as well. In the United States, suppliers of materials, components, equipment, and final products are often different companies, doing business with a range of suppliers and customers. A manufacturer of components may be reluctant to give feedback to a materials supplier because of concern that the information could be passed along to a competitor. In Japan, electronics producers tend to be more vertically integrated, and relationships between suppliers and manufacturers often are conducted on a longer-term basis that deemphasizes short-term price concerns and facilitates greater exchange of information than what often occurs in the United States.

It is these factors, such as relative ability to operate on longer business investment horizons, more collaborative supplier-manufacturer interaction, and others, that have allowed Japanese companies to capitalize on U.S.-invented technologies such as liquid crystal displays (LCDs). The same factors may put Japanese firms in a better position to capitalize on the emerging commercial applications of piezoelectric ceramics than are U.S.-based companies. One advantage that the United States still has in this area that was not true in the LCD case is that U.S.-based firms are still very strong in the HDD business.

An example from AVX's main business shows that, once research-based products are introduced in commercial applications, incremental process improvements can make a much greater contribution to product performance than basic scientific and engineering research. Over the past two decades or so, the capacitance per unit volume of multilayer ceramic capacitors has gone up by two orders of magnitude, whereas improved materials properties went up by only 18 percent. The main factor driving improved performance was the ability to make very thin layers with better reliability at lower cost.

Human resource and research funding issues

Workshop participants identified human resource and research funding issues as key determinants of U.S. ability to capitalize on its superior research base in piezoelectric ceramics in the future. Several participants mentioned that U.S. ability to capitalize on research in this field would be improved if students and academic researchers had a better understanding of the applications context for their work.

This issue is illustrated by participation in U.S.-Japan joint seminars on piezoelectric ceramics held over the past 15 years with U.S. government support from ONR and the National Institute of Standards and Technology (Freiman, 1996). Japanese participants tend to come from industry, whereas U.S. participants tend to come from universities. Although U.S. academic researchers have benefited from insights into what is happening in Japan, the lack of U.S. industry participation in these sorts of exchanges means that U.S. graduate students and other academic researchers may lack important knowledge concerning the technological context for their research.

This is more fundamental than simply asking students to look at factors such as cost and manufacturability. Even before that, researchers need more intimate knowledge of why their research is directed toward solving a given problem or improving a given property. In an area such as piezoelectric ceramics, where there are competing technologies for many applications, students need to learn more about those alternatives and the various trade-offs. Participants agreed that not only students, but the entire academic research enterprise could benefit from this sort of exposure.[4]

Government research funding was another issue discussed by participants, although there was no clear consensus on where the U.S. system is falling short and what needs to be changed. There was some agreement that the United States has been very successful in capitalizing on research leadership in the high performance and mission-critical areas. In civilian areas more likely to yield significant economic benefits, by contrast, several participants believe that the Japanese government has been more effective than the U.S. government in providing stable, long-term funding for research on basic enabling technologies.

OPTICAL SENSING

For the purpose of this study, optical sensing is defined as the use of light to detect a substance or property other than photons.[5] Therefore, optical detectors, such as photodiodes, are excluded from the definition. Optical sensing systems can be generically described as consisting of a light source, a photodetector, some way of transmitting the light from the source to the detector, and a modulator region where the quantity being detected (pressure, temperature, or a chemical) interacts with the light and produces a change in the characteristics of the light. Any of the characteristics of light (amplitude, frequency, phase, polarization state) can be utilized in the sensor.

Optical sensing research is inherently interdisciplinary and driven by applications. Knowledge from electrochemistry, analytical chemistry, optical spectroscopy, and optoelectronics is drawn upon. Note that a generic description of optical communication systems is similar to that of optical sensing systems, with both

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[4]For example, Michael Cima first became interested in the HDD applications for piezoelectric ceramics, an issue outside his specialty, through discussions with a Master's student at MIT who was working for a supplier to a stack actuator manufacturer.

[5]This section is based primarily on the presentations of Michael Butler and John Woodward at the COSEPUP Workshop on Piezoelectric Ceramics and Optical Sensing, Washington, D.C., May 23, 1996.

requiring a light source, a detector, and a way of putting information on the light beam. Components being developed for optical communications are available for optical sensing. Because optical communications is a multibillion-dollar industry, companies are willing to devote significant resources to develop the necessary components, such as optical fibers, laser diodes, and photodetectors.

Optical sensing as an industry is small and fragmented, and so, capital is not readily available to develop dedicated component technologies. The ability to draw on communications-targeted advances is an important advantage. However, components developed for communications may not have the optimal characteristics for sensing applications. For example, several of the parameters of optimal light sources are different for communications and sensing.

The focus of the workshop discussion was on fiber-optic sensors. There are three basic types that use the fiber as a sensor (see Figure A-2) and a fourth that uses the fiber to route light from the sensing end or probe to the spectroscopic instrument. Intensity sensors are useful for detecting pressure or forces. An optical fiber is inserted in a double jawed chuck. As pressure is applied, the bend radius of the fiber gets smaller, and so less light is transmitted. A bimetallic strip also can be utilized. The strip intercepts part of the beam and, as the temperature changes, the strip bends, intercepting more or less light.

A second type of optical sensor is polarimetric. The fiber is rotated with magneto-optic or electro-optic materials to detect magnetic or electric fields.

A third type of sensor is interferometric, such as a Mach-Zehnder interferometer. One of the fibers is coated with a magnetorestrictive material to make a magnetic-field sensor. It can be coated with a substance that will react with the substance to be detected. Most chemical fiber-optic sensors use this mechanism.

A fourth type of sensor uses the fiber to route light from an optical probe end to a spectroscopic instrument. These types of sensors are used to measure trace species and antibodies in blood or the concentration of chemicals in a process flow.

Thus far, optical sensors have not been utilized widely because fiber optics and other components of the system are expensive. In areas where another sensor technology is well established, a new approach needs to carry a significant cost or performance advantage to gain a foothold. Therefore, applications of optical sensing have been limited so far to areas where the technology has unique advantages. Optical sensors are not affected by electromagnetic interference (EMI), do not require wires (a safety issue in biomedical applications), are easily multiplexed, can be utilized for remote applications (there is no loss of performance kilometers away), are lightweight (important for aerospace applications), and operate over large bandwidths. Although optical sensing is a small and fragmented business today, experts at the COSEPUP workshop expressed the view that, as costs come down, optical sensors will replace other technologies in a wide range of applications in the future.

Research and applications leadership

There are three major research communities in optical sensing: the United

States, Europe, and Japan. It is somewhat difficult to say who is ahead or behind in research because the field is so broad and fragmented. The United States is ahead in areas driven by particular applications, such as space and health care. Although one participant expressed the view that Europe might be ahead overall, an examination of the production of research papers shows that the United States produces a large share of the world's research in terms of volume. In addition to work at universities, work at U.S. national laboratories is also significant in this field. The experts agreed that work in Japan is more oriented toward applications than is work in Europe or the United States.

The United States leads in research in several areas driven by government interest in specific applications. There are several promising applications in the

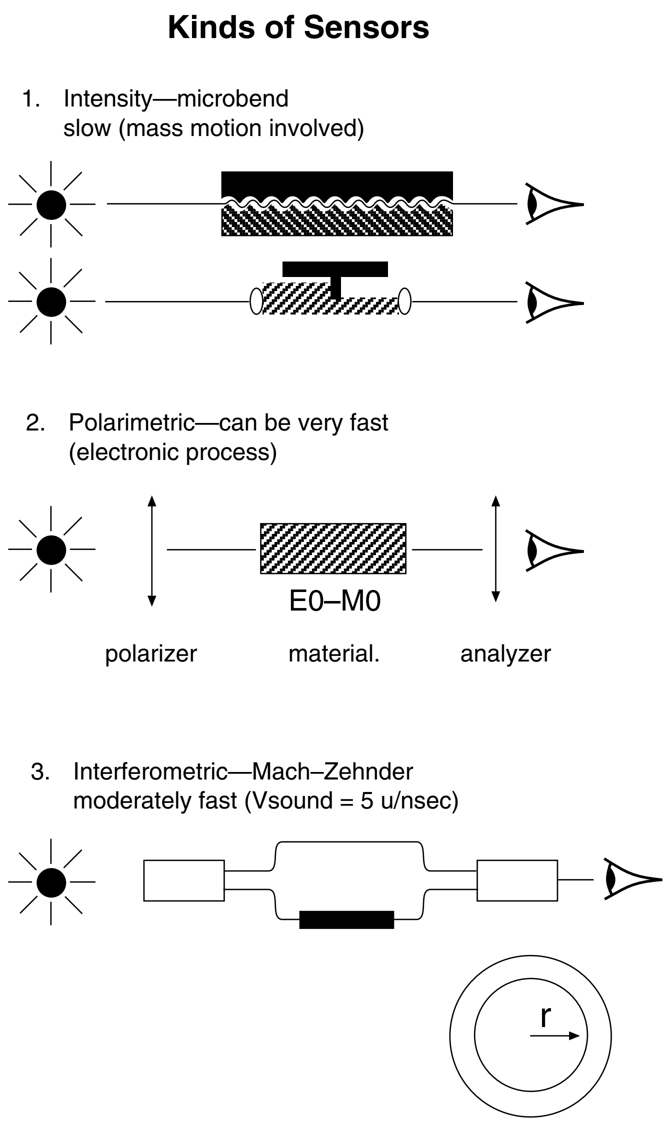

Figure A-2.
Source: Michael Butler.

defense area. One is use of optical sensors in conjunction with "fly by light" actuation for aircraft control surfaces. Actuation traditionally was accomplished through hydraulic systems and, more recently, "fly by wire" actuation through electronics has become utilized widely. The military driver for fly-by-light is the increased use of composite materials in aircraft, which provides less protection for control systems against EMI. Because fiber optics are not affected by EMI and are also lighter, fly-by-light has several key potential advantages over fly-by-wire. Optical sensors would be key components of any fly-by-light system.

Another military-derived application is in fiber-optic hydrophones. DoD has invested considerable sums to develop towed fiber-optic arrays for naval vessels, aimed at detecting submarines. Work is now under way to adapt these systems for commercial applications, such as oil exploration. DoD has had a considerable impact because it has been willing to provide funding all the way from very fundamental work to applications, reducing the commercialization risk because the end product is known.

No country or company has yet capitalized heavily on optical sensing research in terms of developing successful applications for large markets or to advance other societal needs. Work on research and applications is moving in interesting directions, highlighting strengths and potential weaknesses in U.S. approaches compared to those of other countries.

Capitalization

As noted in the preceding section, most existing applications of optical sensing take advantage of unique aspects of the technology. For example, fiber temperature sensors have gained some acceptance in the food processing industry, particularly where microwave ovens are used, because of the absence of wires. In the electric utility industry, there are many potential applications such as monitoring currents, monitoring transformers, and distributed temperature monitoring for hot spots. Here, the EMI immunity of optical sensors is an advantage.

Health care applications also have received attention. Puritan-Bennett invested considerable resources in developing a sensor to simultaneously monitor several characteristics of blood (CO_2, O_2, and pH) which was ultimately unsuccessful. Other U.S. companies have continued work in this area, and the price of these systems is falling to near the level at which they might gain widespread market acceptance. Ingold, a division of the Swiss chemical company Ciba, is very strong in the area of blood oxygen sensors, and may be better positioned to capitalize on any major innovation than U.S. companies.

Besides DoD-funded work, one of the important pathways for capitalizing on optical sensing research is by small companies, often working with university researchers. The workshop participants mentioned several times that the Small Business Innovation Research (SBIR) program has been an important source of support for these efforts. Because optical sensing research is a fragmented field, there is no focus on research funding by a particular agency. The targeted initial markets are often small, making large companies uninterested in pursuing them.

SBIR support helps small companies to develop their innovations, and also plays a role in validating their technology for venture investors.

One advantage that the United States has had in this area is the relative ease with which researchers can work with industry. Links can be very direct. For example, an industry R&D manager typically will go to a conference, see an interesting presentation, and then invite the researcher to give a talk at the manager's company. There are signs that this open environment may be changing and that, as universities become more concerned about protecting intellectual property rights, exchanges may require more formal preconditions. Opportunities to learn of new developments through serendipity may decline. This is a particularly important point for optical sensing because it requires lateral thinking and the ability to capture and integrate knowledge from a number of different fields.

Future directions

The workshop participants identified several research directions that could lead to important developments in the future. One area is the combination of optics and microfabrication, particularly silicon-related work on MEMS. The ultimate goal is the development of microinstruments. A group at Sandia National Laboratory has focused on microchemical sensors. Up until now the focus has been on discrete sensors in which a coating on the fiber optic would transduce the chemical to be detected into a signal. However, it is difficult to discriminate whether one chemical or a similar one is present if they both react similarly to the coating. Several approaches are being explored to overcome this difficulty, such as molecular recognition and highly specific binding sites, and development of a mass spectrometer on a chip.

Chemical sensors are a particular area of focus for optical sensing research, even outside the MEMS area. For example, periodic gratings are being developed to see the absorption characteristics of molecules. Chemical sensors for corrosive species or dangerous chemicals could eliminate use of reference cells.

Cost is a major issue in developing a product with wide acceptance. For example, several companies have developed a charge-couple device (CCD) spectrometer, but a computer is still required to run it. Interesting work is being done to use modified commercial camcorders, which utilize CCDs, to lower the cost of optical sensing systems.

Research funding and human resource issues

Participants mentioned a number of relevant policy issues, several of which have emerged in the examination of other cases.

First, concern was expressed that U.S. government basic research funding is becoming too conservative. Although no hard evidence was presented, several participants expressed the view that funding is increasingly directed toward areas where the answers are already known, and not enough is being spent on truly fundamental work. This may be part of an international trend in which research funding and performing organizations are increasingly scrutinized and asked to measure and report concrete results. In optical sensing, a field that does not have a dedicated source of funding and where most work is applications oriented to begin with, maintaining the level of funding for fundamental work is seen as critical.

Interestingly enough, this stress on the importance of fundamental research was coupled with doubts about whether the United States really does benefit differentially from its research leadership in optical sensing. Because this is a field in which insights from various scientific fields need to be combined, there is an inherent tendency to look outside the organization to the wider research community. Researchers in optical sensing may expend more effort in tracking global developments.

A second point raised by participants was that tighter industry-university links in research and education would be helpful. One mechanism used in some European countries is government subsidization of a three-year university-industry postdoctoral research program. The student is hired by the company and alternates between the company and an academic lab. This helps the company to stay linked to fundamental research developments and allows the student to gain familiarity with industry problems. One participant noted that, in the context of optical sensing work in the United States, such a program would be particularly useful if it was targeted at smaller companies.

CATALYSIS

A catalyst is a substance that speeds up a chemical reaction without itself being consumed in the process. Over 90 percent of the currently practiced processes in the chemical and petroleum industries depend on one or more catalysts (Bell, 1997). These industries contribute over $700 billion to the Gross Domestic Product and employ over one million people.

The development of new catalysts and catalytic processes is a continuing focus for the chemical and petroleum industries for several reasons. Better catalysts can improve the efficiency of existing processes by allowing more of the desired product to be produced from a given amount of reactant materials, or by allowing the process to take place at lower temperature or pressure. New catalysts can enable the utilization of cheaper feedstocks, which also reduces cost. Novel catalytic techniques can make possible new processes and the synthesis of new chemicals or materials with unique, desirable properties. Finally, developments in catalysis can lead to improved processes in which the resulting waste products are less hazardous or even useful.

Many types of materials can serve as catalysts, including metals, compounds (metal oxides, sulfides, nitrides), organometallic complexes, and enzymes (Board on Chemical Sciences and Technology, 1992). There are several different types of catalytic processes. A homogeneous catalytic process is one in which the catalyst is in solution with at least one of the reactants. In a heterogeneous catalytic process, the catalyst is in a different phase (usually solid) from the reactants (generally gas or liquid). Heterogeneous processes often are preferred because the catalyst can be separated easily from the products and reused. The catalyst can be in a porous form so that the reaction takes place in the pores, or in a monolithic state in which the reaction takes place on the surface. In a supported catalytic reaction, small particles of the active material are spread over a less active substance, whereas an unsupported reaction does not utilize a less active substance.

The first commercially utilized catalytic process was developed in Germany early in this century, and utilized iron to catalyze the synthesis of ammonia (NH_3) from nitrogen and hydrogen (Board on Chemical Sciences and Technology, 1992, p. 3). Other important developments in catalysis over the years include Monsanto's process to selectively produce the active left-handed isomer of L-Dopa, a drug used to treat Parkinson's disease, and the emergence of catalytic converters that remove exhaust gases from automobile emissions.

At the February 1997 workshop on Capitalizing on U.S. Research in Catalysis, the discussion covered several subareas of catalysis, and raised more general issues important to the field and the overall capitalizing study.

Zeolites and molecular sieves

Zeolites are the most widely used type of molecular sieve, which are inorganic solids that can organize and react molecules with an angstrom-level specificity (Davis, 1997). In addition to being used in chemical reactions, zeolites are commonly used in detergents. Zeolites have pores of absolutely uniform sizes in the range of a small molecule, the current state of the art for pore size being 12 Å or below. Zeolites have been studied and utilized since the 1950s. Much of the early research and application focus was on crystals of silicon and aluminum oxide. In the 1980s, researchers began experimenting with other materials, and a number of new zeolites have emerged. The use of different materials produces different structures with different-size pores.

Zeolites are used in several ways. A zeolite with reactant shape selectivity is used if one of the reactants is to be allowed into the crystal and others kept out. A zeolite with product shape selectivity lets only certain-sized products out of the crystal. In a reaction with more than one transition state, a zeolite with transition-state selectivity will not allow one of the states to form. The zeolite's active site is produced by the framework element, such as aluminum or titanium.

Zeolite catalysis has been used widely in the petrochemical area but is just beginning to emerge in the production of higher value-added materials such as fine chemicals and pharmaceuticals. Workshop participants observed that, over the past 15 years or so, research leadership has moved from U.S. oil companies to U.S. universities, although a number of foreign universities and companies have excellent research efforts under way.

Because of the growing demand for environmentally benign processes, and the research advances of the past decade that have allowed the development of zeolites that can catalyze a broad spectrum of reactions, zeolites are well positioned for wider application. A few examples were discussed that illustrate this promise. One is the use of platinum-based Pt-zeolite for the L-aromatization of *n*-hexane to make benzene. This is a much more efficient way to make benzene than previous processes. The process was first reported in 1980 and subsequently commercialized by Chevron.

Another example illustrates how zeolites can be used in more environmentally benign processes. Cumene is a material used to make resins. Cumene synthesis is accomplished in the liquid or gas phases, and can lead to corrosion, leaching, or disposal problems. There are now at least five commercial processes using zeolites to produce cumene that have emerged in the past few years, including a process introduced by Dow Chemical in 1992, which are running very well and are reducing the environmental problems.

It is inherently challenging to replace traditional stoichiometric processes with zeolite catalysis for making pharmaceuticals and fine chemicals, because of the complexity of the molecules that are being synthesized. Incentives to lower production costs and environmental impact traditionally have not been as pressing as is the case with large-volume petrochemical or commodity chemical products. Yet the cost-benefit equation is changing with the emergence of new zeolites. One example is Hoechst's new route to making the anti-inflammatory ibuprofen. The process takes only three steps, which are all catalytic. One workshop participant remarked that European pharmaceutical and chemical companies appear to be more aggressive than are U.S. companies in developing these new processes.

Trends in zeolite research and capitalization raise a number of important issues. Applications traditionally have been driven by industry, without a great deal of industry-university interaction in research. However, a number of the U.S. oil companies cut back their zeolite research in the 1980s, whereas research in U.S. universities has become much stronger. Now that U.S. university work is increasingly ripe for capitalization, it appears that European and Japanese companies are more interested in working with U.S. universities than are U.S. companies.

Workshop participants discussed several possible reasons for this trend. Research and development at U.S. chemical and petrochemical companies has become focused increasingly on shorter-term problems and outcomes, making companies less interested in working on fundamental problems with universities. This short-term orientation also means that intellectual property rights issues can arise as a barrier to U.S. industry-academic collaboration.

Single-site olefin polymerization catalysts

Leaving aside hydrocarbons, polymerization is the largest application of catalysis (Goodall, 1997). In contrast to zeolites, where developments have been driven by industry, every milestone in the past 40 years in polymerization was made in academia. In 1953, German chemist Karl Ziegler discovered a new technique for catalyzing the synthesis of polyethylene. European academics, including Ziegler and Italy's Julian Natta, led the way in making discoveries of better catalysts, such as $TiCl_4$ and $TiCl_3$, to make polyethylene, polypropylene, and other polymers of a specific tacticity from monomers such as ethylene and propylene. Interestingly, many of the most important discoveries were made accidentally, and we still do not have a complete understanding of how Ziegler-Natta catalysts work.

Ziegler-Natta polymerization has some limitations. For example, it does not work with some monomers, or when a functional group is incorporated into the monomer (as in the synthesis of polyvinyl chloride).

Recently, a new type of polymerization, also using metal complexes as initiators, has been developed, called metallocene catalysis polymerization. Metallocenes are homogenous catalysts and are not new themselves. The name goes back to 1954, with the development of ferrocene, which consisted of two C_5 rings around an iron atom in a sandwich structure. Metallocenes were used as components of Ziegler-Natta catalysts from the 1950s, with a number of research developments emerging from academic labs during the 1960s and 1970s. Germany had several of the world's best research groups during this period.

Since the late 1980s, the applications of metallocene catalysts have expanded greatly, and research promises that this growth will continue. Metallocenes are single-site catalysts because each molecule contains a single metal atom at the core as an active site. This encourages molecules to connect with each other in a highly predictable way. Single-site catalysis allows the development of new forms of polymer materials with very specific features. Research advances are beginning to allow the rational design of catalysts and materials. Metallocenes allow unprecedented control over the microstructure and molecular weight of the product material.

The limitations of the technology include the inability to polymerize monomers bearing functional groups, with very few exceptions. Metallocenes are very expensive, and it likely will be years before they are used to produce commodity materials.

The leading research in academia is now done in the United States, with outstanding groups at California Institute of Technology, Stanford, University of Iowa, and several other places. Companies from around the world are competing to apply metallocene catalysts, including Exxon and Dow Chemical in the United States, Fina in Italy, British Petroleum, Hoechst in Germany, and Mitsui Petrochemical in Japan.

Another recent development is the emergence of catalytic materials that are cousins of metallocenes but are based on transition metals such as nickel and palladium. DuPont, the University of North Carolina, W.R. Grace, BFGoodrich, BP Chemicals, California Institute of Technology, and Shell Chemicals are doing leading-edge work in this area. These new transition-metal catalysts overcome some of the disadvantages of metallocenes, most notably the inability of metallocenes to incorporate functional groups.

One of the U.S. Department of Commerce's Advanced Technology Program (ATP) focused programs in recent years was in the area of catalysis, including transition-metal single-site catalysts.

Other metal and metal oxide catalysts

In metal and metal oxide catalysis, 80 percent of the reactions are heterogeneous, many were discovered by accident, and many are not well understood

(Warren, 1996). At the active site the metal or metal oxide breaks bonds and provides oxygen. The support material, which also may be a metal oxide, disperses, coordinates, and stabilizes the active metal. A promoter material tunes the metal oxidation state, blocks unselective reactions, and creates active sites.

Important reactions using metal and metal oxide catalysts include selective partial oxidations. For example, in a reaction known as epoxidation, a silver metal catalyst supported by alpha-alumina with promoters is used to produce ethylene oxide from ethylene. Much of the current effort in metal and metal oxide catalysis is aimed at replacing light olefins, such as ethylene and propylene, with cheaper feedstocks such as alkanes. Another area of effort is complete oxidation (combustion) reactions.

A group of 12 academic and industrial catalysis researchers was polled informally for their views on U.S. performance in research and capitalization. The group consisted of seven academic and five industry researchers; five chemical engineers, and seven chemists. The sense of the respondents is that the United States enjoys research leadership today and is effective, particularly in the characterization of new catalysts.

However, several respondents see the United States as being in a state of decline relative to Europe. The short-term orientation of U.S. industry and the barriers to enhanced university-industry collaboration were mentioned. Both industrial and academic laboratories appear to prefer collaborations overseas. On the other hand, respondents see U.S. academic research and education as very strong. Several respondents from industry believe it would be helpful if students could gain more experience and insight into industry problems.

Biocatalysis

The term *biocatalysis* refers to the utilization of enzymes as catalysts (isolated and whole cells) (Drueckhammer, 1997). Enzymes are proteins that act as organic catalysts, and are essential to many of the chemical reactions needed to sustain life. Several of the research breakthroughs needed to utilize enzymes as catalysts were made in the late 1970s. The pioneers in this work are still active but most have moved on to work in other areas.

One problem blocking use of enzymes as catalysts is that they are unstable compared to molecules. This disadvantage has been overcome to some extent. Enzymes are also very specific in terms of the support material required and the reactions that a given enzyme will catalyze, but this can be an advantage in some places. Enzymes are expensive, but in the long term can bring down costs of processes. Still, they generally are viewed as being limited to small-scale, high-value applications. Enzymes work best in water, rather than in organic media.

One example of enzyme utilization is as proteases in detergents. Other applications are in the food industry. For example, in making high-fructose corn syrup, enzymes are used to convert starch to glucose and glucose to fructose. Enzymes also are used to produce amino acids. Most of these applications were developed by industry before academia was interested.

Future applications include the isolation of the effective isomer in a racemic compound, similar to the applications of zeolites discussed earlier. Enzymes also may be used in "metabolic engineering," such as the production of analog streptomycenes by "engineered" microorganisms.

Compared with several other areas of catalysis examined at the workshop, biocatalysis is one area in which small start-ups are relatively important. Some small companies make enzymes, such as Altus (a subsidiary of Vertex), Thermogen (has isolated enzymes from materials that grow at high temperatures in order to overcome stability problems), and Amano (a supplier of enzymes to the food industry). Large pharmaceutical companies are also active in some areas of research, as are biotech companies such as Celgene and Sepracor.

There is much less work in academic research now than during the 1980s, because of a sense that the most important academic problems have been solved. The most important tasks for industry are to make enzymes more stable or to develop enzymes that work in organic media. These are essentially engineering problems that companies attack using people who possess traditional synthetic chemistry backgrounds. There is not a large demand for people with advanced degrees who specialized in biocatalysis.

Issues and lessons

Unlike several other fields examined for this study, catalysis research has not been heavily supported by the federal government, either DoD or other mission agencies. The United States has not enjoyed clear research leadership across the board, but U.S. companies generally have been well positioned to capitalize on research, and U.S. universities have maintained a critical mass of talent and activity.

In recent years, academic interest in some areas of catalysis has been declining relative to surface science, particularly in chemistry departments. Still, U.S. universities, particularly chemical engineering departments, have emerged at the forefront of research. U.S. industry, particularly the oil companies, have cut long-term catalysis research. Foreign companies have long been effective at capitalizing, and remain so. Because many of the important tasks in catalysis are incremental and long-term, the field is not attractive to start-up companies and venture capital.

Particularly in the most rapidly emerging subfields of catalysis, there is clearly a growing commonality of scientific interest between U.S. industry and U.S. universities. As in most of the fields examined for the study, the university-industry interface will likely emerge as the most important element in U.S. capability to maintain research leadership and capitalize on that leadership. However, the workshop discussion uncovered a number of barriers to closer cooperation within the United States in areas such as treatment of intellectual property and the expected time horizons for results. Although some U.S. companies and universities are forging closer ties, workshop participants observed that, in some areas, U.S. industry and academia often find it easier to work with foreign partners.

The idea that the federal government can play a positive role in fostering closer and more effective university-industry ties resonated among participants, but there were differences in perspective over how to accomplish this. Some participants were positive about initiatives such as the ATP Focused Program on Catalysis and Biocatalysis. Others favored initiatives that would more directly involve universities. For example, catalysis is not the focus of any special continuing federal research effort such as the Engineering Research Centers or Science and Technology Centers of NSF.

Finally, a number of participants observed that education and human resource issues are critical, as was true for just about all of the other cases. The general sense of the workshop discussion was that the United States does a good job of training students relative to that of other countries. Although demand for chemists and chemical engineers focused on some areas of catalysis has been slack, their skills and knowledge are often transferable to other areas, such as surface science, where the electronics industry has a growing demand for talent. There were differences of perspective over whether the lack of jobs in catalysis research should be seen as a negative, or whether the flexibility of students should be seen as a positive.

EXAMPLES OF JAPANESE CAPITALIZATION ON EXTERNAL RESEARCH

This section describes several cases in which Japan has capitalized on research performed elsewhere: the basic oxygen steel process, numerically controlled (NC) machine tools, and LCDs.

Basic oxygen steel process

Developed in Austria in the early 1950s, the basic oxygen process uses pure oxygen rather than air to convert molten iron into steel.[6] It allows higher productivity and the utilization of a wider range of raw materials than earlier processes.

During the 1950s, Japanese engineers did not have as many resources to stay abreast of global technological developments through travel and technical journals as did Western engineers. Japan's trading companies played a significant role by gathering information about the oxygen steel process and disseminating it to steel companies. By 1955, Nippon Kokan and Yawata Steel had learned enough about the process to became interested in licensing it, and approached the Ministry of International Trade and Industry (MITI) for foreign exchange approval to conclude licensing agreements.

MITI brokered an agreement whereby Nippon Kokan would be the principal licensee, but would sublicense the technology to other Japanese steelmakers. This was a common MITI practice, which lowered the overall price to Japanese industry of critical foreign technologies. MITI and the steel industry also set up the Basic Oxygen Committee in 1956 to act as a clearinghouse for information exchange about the new process. The committee held regular meetings and facilitated informal contacts among engineers.

[6]This account is based on the account by Tessa Morris-Suzuki (1994, pp. 189-191), who, in turn, bases much of her account on that of Lynn (1982).

At the same time, individual companies were competing to refine and adapt the process. Japanese steel companies worked with firms in related industries to develop complementary innovations. For example, the new process caused the refractory bricks lining the new converters to wear out very quickly. Yawata Steel and Kurosaki, a refractory brick maker, developed an improved brick.

More rapid adoption of the basic oxygen process than that by U.S. and European steel companies was a factor contributing to the success of the Japanese steel industry over the next several decades. In 1960 the Japanese steel industry was only half as productive as the European industry and one-third as productive as the U.S. industry. By the early 1980s, Japanese productivity in steel had overtaken that of the United States and Europe.

The Japanese steel industry had several advantages, such as rapid growth in demand for steel, which gave Japanese firms more opportunity to build new plants with modern technology. Still, this case illustrates the effectiveness of Japanese institutions such as trading companies, industry associations, collaborative research, and government coordination, in scouting, importing, diffusing, and improving foreign technologies during the postwar period.

NC machine tools

Numerical control, which allowed machine tools to be automated, was developed in the early 1950s by a subcontractor to the U.S. Air Force in cooperation with researchers at MIT.[7] An MIT report on NC machinery was brought to Japan by a Japanese professor working at the University of California, and publicized by an industry research association.

Several companies and universities in Japan started working on NC technology. Fujitsu, a telecommunications equipment company, set up a team to work on the technology, and produced a prototype NC turret punch press in 1956. Fujitsu began to work with other machinery companies to develop the technology further. Japan's first commercial NC tool was developed by Fujitsu, Hitachi, and Mitsubishi Heavy Industries for use in the latter's Nagoya aircraft factory. Fujitsu set up its Fanuc subsidiary to focus on NC technology in the late 1950s.

During the 1960s, Fanuc played a key role in incorporating advanced electronics, first transistors and then integrated circuits, into NC controls. Fanuc and other Japanese companies also continued to stay abreast of research developments in the United States and actively licensed technologies. Because of cost reductions enabled by use of microelectronics and other factors such as rapidly rising labor costs and growth in Japan's machine-tool demand, a significant market for relatively inexpensive general-purpose NC tools developed among Japan's small manufacturers during the 1960s and 1970s. MITI and regional governments set up programs to promote technical information exchange and provide assistance to small manufacturers, which also fed this growth.

[7]This account is based on Morris-Suzuki (1994, pp. 199-202), who in turn cites Friedman (1988), as well as Japanese language sources.

In contrast to developments in Japan, U.S. machine tool makers focused their NC product offerings on highly sophisticated customers, a profitable but relatively small market. By the time smaller U.S. manufacturers began to demand NC tools, Japanese companies were better positioned to supply them. The Fanuc NC controller became the industry standard. By 1983, Japan led the world in machine tool production.

LCDs

Liquid crystal materials were discovered in 1888 by F. Renitzer, an Austrian botanist.[8] In 1963, George Heilmeier and other researchers at RCA discovered that electrical charges affect how light passes through liquid crystal materials, and they began work to develop an electronic display that would utilize liquid crystals. By 1966, they had demonstrated the first prototype liquid crystal alphanumeric displays in instruments and cockpit applications as well as digital voltmeters and digital clocks. These prototypes were shown to the world in 1968. The ultimate goal was to develop a liquid-crystal flat-panel television that could be hung on a wall. Although RCA was able to demonstrate the technology, it lacked a liquid crystal material that would remain stable at room temperature in the nematic phase in which the display could function. George Gray, a professor at Hull University in England, made the key discovery of cyanobiphenyl materials that exibited room-temperature nematic phases. Several European firms developed and patented these materials, and continue to hold a strong position in supplying liquid crystal materials today.

At the same time that RCA was developing its flat television prototype, the electronic calculator industry was growing rapidly, enabled by developments in microelectronics. American and Japanese companies were at the forefront of this industry, and extensive business and technological ties developed. For example, Intel developed the first microprocessor for use in a calculator made by Busicom, a Japanese firm that has since gone out of business. Rockwell International sold key calculator components to Japan's Sharp, which assembled them.

In the early 1970s, leading calculator companies were searching for an appropriate display technology to use in hand-held units. The display would need to be visible in ambient light and not consume an excessive amount of power. Rockwell and Texas Instruments both did work on LCDs. Combining insights from its own work, exposure to Rockwell's work, and technology licensed from RCA, Sharp produced the EL-8025, which it claims is the world's first electronic calculator using an LCD. Rockwell also produced a calculator with an LCD at around the same time, but soon exited the calculator business because it was a low-margin activity outside the company's core military and space work.

[8]This account is based mainly on a telephone interview with Lawrence Tannas on November 25, 1997. It is supplemented by material from Tannas et al. (1992) and material from the Sharp Corporation World Wide Web page.

Although light-emitting diodes emerged as the display technology of choice for hand-held calculators during the 1970s, LCDs emerged again in the late 1980s with major advantages as a display technology in the rapidly growing electronic watch business. A number of U.S. and Japanese companies entered the LCD business during the latter half of the 1970s. However, the technology was widely available and straightforward, and so, U.S. companies tended to move manufacturing to offshore locations when it became cost-effective to do so. Japanese companies, including Suwa-Seiko (now Seiko Epson), Sanyo, Canon, and others, were more inclined to see such component technologies as fundamental capabilities for a range of consumer-oriented electronics businesses and long-term growth.

As was the case with NC tools, Japanese companies continued to supplement their own incremental improvements of LCD technology with insights gained from foreign research. In 1983, Sanyo and Suwa-Seiko demonstrated the first twisted nematic active matrix LCD (TN-AMLCD). The use of a poly-silicon semiconductor substrate was a key improvement pioneered by Sanyo and Suwa-Seiko. However, amorphous silicon soon dominated the industry. The target market at that time was hand-held televisions, first black and white and then color.

The super-twisted nematic LCD (STN-LCD) was first reported by European researchers Terry Scheffer and Juergen Nehring in the early 1980s (Scheffer and Nehring, 1990). STN-LCD became the dominant technology for manufacturing portable computer displays, an application that emerged in the second half of the 1980s and is now a multibillion-dollar business. The TN-AMLCD using amorphous silicon became the major display technology in the 1990s for notebook computers and hand-held televisions. Technologies other than LCDs were tried in portable computers, but all have been replaced with LCDs as STN-LCDs and TN-AMLCDs have continued to improve their performance as costs have declined gradually. Japanese firms have dominated this business, although Korean, and to a lesser extent Taiwanese, companies have entered in recent years and appear to be enjoying significant success.

In the LCD case, as in basic oxygen steel and NC machinery, Japanese companies displayed adeptness in incorporating new component technologies in a variety of products, enabling the emergence of larger mass markets. Long-term efforts on complementary technologies enabled Japanese industry to capitalize on foreign research. The role of Japanese government and industry research laboratories in gathering information and diffusing technology to individual companies is apparent in the LCD case.

FUZZY LOGIC

Fuzzy logic is a field of research and application in which fundamental discoveries made in the United States were first reduced to practice and capitalized on overseas. Fuzzy logic is a system for representing and manipulating values associated with vague or uncertain concepts, such as "large," warm," and "fast," which can be seen simultaneously to belong partially to two or more different, contradictory sets of values (JTEC, 1993). In contrast to traditional logic, which represents objects in terms of sharp distinctions, fuzzy logic allows an object to be represented as a member of a class in a graded way.

Fuzzy logic was invented by Lotfi Zadeh, a professor at the University of California at Berkeley, in the 1960s. Researchers in the United States and abroad began developing applications for fuzzy logic. In 1973, at Queen Mary College/ London University, Ebrahim Mamdani and Sedrak Assilian applied fuzzy logic to the control system of a small steam engine. Lauritz Peter Holmblad and and Jens-Jorgen Østergaard, corporate engineers at F. L. Smidth (now FLS Automation), learned of this work and began research on an automatic cement kiln control system utilizing fuzzy logic in the mid 1970s (McNeill and Freiberger, 1993). In 1980 the first high-level kiln control system became commercially available, supplied by FLS.[9] Today, most cement kilns use fuzzy logic control (L. Zadeh, University of California at Berkeley, personal communication, June 30, 1998).

Fuzzy logic caught on quickly in Japan, perhaps because of a cultural tolerance for uncertainty. In 1968, papers on fuzzy logic began to appear in Japanese journals. In 1972, Professor Toshiro Terano of Hosei University introduced fuzzy logic to the research community in Japan and several study groups were formed. This led to research and applications mainly in the area of physical systems control.

In 1987, after eight years of development, the fuzzy-controlled Sendai Subway system went into operation (McNeill and Freiberger, 1993, p. 155). The system was developed by Hitachi. Besides featuring an extremely smooth ride, the subway stops and starts more accurately than a human-operated train, and cuts energy usage by 10 percent. By 1990, fuzzy logic had been implemented in a wide range of home electric appliances in Japan (Munakata and Jani, 1994).

In contrast to researchers in Europe and Japan, who were receptive to applying fuzzy logic, progress has been slower in the United States (JTEC, 1993). Important segments of the U.S. research community have been indifferent or hostile to fuzzy logic. Although mathematical work on fuzzy logic continued in the United States, the interested community was isolated. More practical, engineering-oriented work was slow to develop.

Zadeh himself, who has remained an active and effective advocate for his ideas, believes that discomfort with the word "fuzzy," the American tradition of respect for precision, and an entrenched establishment of control system techniques all prevented the U.S. research community from embracing the theory (L. Zadeh, University of California at Berkeley, personal communication, June 30, 1998). Engineers in industry working on controls for various products have been skeptical that fuzzy logic could deliver better performance than effective implementation of traditional "crisp" logic. By contrast, there was less entrenchment in Japan and an eagerness for new ideas, which facilitated commercialization.

Currently, fuzzy logic is applied in a broad range of commercial products, such as automobile climate control and transmissions, microwaves and dishwashers, and other control systems. U.S. industry has become more receptive to utilizing the

[9]FLS web site, http://www.flsautomation.dk

technology in recent years. U.S. firms, such as Otis Elevator and Motorola, that are active in the Japanese market and eager to respond to their Japanese customers' interest in fuzzy logic, are most advanced. The United States is still among the leading centers of research, with excellent work being done at institutions such as Georgia Institute of Technology and the University of New Mexico.

CAPITALIZING IN THE SOCIAL SCIENCES

Although this report focuses on capitalization in the natural sciences and engineering, research capitalization also occurs in the social sciences. Two examples from the field of economics illustrate the successful application of social science theory to real-world problems.[10] Research in the area of options pricing has been applied to risk management and has helped to make a new exchange system successful. Game theory has been applied to spectrum license distribution, with the result of increased profits for the government and more efficient distribution of licenses.

Options pricing

In 1997, Robert C. Merton and Myron Scholes won the Nobel Memorial Prize in Economic Sciences for their work on the pricing of options. Myron Scholes and Fischer Black created a formula, first published in the *Journal of Political Economy* in 1973, relating options pricing to asset price volatility and time. Simultaneously, Robert Merton had applied these results to other types of financial assets. The Chicago Board of Options Exchange (CBOE) opened for business that same month.[11] This theory provided an efficient way to manage risk in stock portfolios, which has increased participation and improved liquidity. The presence of the theory makes the market more predictable and therefore more easily and more widely used, enhancing the value of exchanges. "Corporate strategists use the theory to evaluate business decisions; bond analysts use it to value risky debt; regulators use it to value deposit insurance; wildcatters use it to value exploration leases. In fact, the model can be used to examine any 'contract' whose worth depends on the uncertain future value of an asset" (*The Economist*, 1998).

The first application and growth in this area took place in the United States.

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[10]In the social sciences, as in the natural sciences, a research advance that is successfully capitalized is not necessarily a success in every single use of what was learned from the research. Some attempted applications of fundamental knowledge founder even when there have been many successful uses. Two such examples have arisen with the applications discussed here. Long-Term Capital Management (LTCM), a hedge fund whose partners included the economists awarded the Nobel Memorial Prize for their work on options pricing, experienced huge losses and almost collapsed before the Federal Reserve Board worked with LTCM's creditors to work out a rescue plan. See *The Economist* (1998). Also, the Federal Communications Commission's successful auction program suffered a setback when procedures aimed at encouraging bidding by industry newcomers in a May 1996 auction backfired. A number of the winning bidders were subsequently unable to pay for the licenses. See Mills (1998).

[11]www.cboe.com/cboe25th/news.html

The basic research was done in Boston during the 1970s. The CBOE opened in 1973 and, by 1997, four U.S. options exchanges were trading more than 350 million options contracts on 2,400 individual stocks. There are over 50 options exchanges in the world where options pricing based on the Black-Scholes equation is widely used.

Spectrum auctions

From July 1994 to May 1996, the Federal Communications Commission (FCC) conducted six auctions for the distribution of radio spectrum licenses for wireless technologies. The system devised for these auctions was based on economic theory. The FCC enlisted John McMillan, an expert in game theory and economist at the University of California at San Diego, to apply the principles of game theory to help optimize the sale of licenses.

Game theory was created by mathematician John von Neumann and economist Oskar Morgenstern during the 1940s. Research on game theory was funded during the 1950s and 1960s by DoD, and it has become increasingly important in political science.[12] Game theory is suited to highly structured situations, such as auctions. Auction theory is an application of game theory that was first developed for single-item auctions. William Vickrey received a Nobel Memorial Prize for critical analysis in this area. Recent advances in auction theory are for simultaneous multiple-item auctions and the use of experimental economics to design an auction in a way that helps people to reach the predicted equilibrium. Auction theory can be used to help people decide how to bid in an auction and also to design an auction so that the equilibrium will be as efficient as possible.

Several other academics helped to design the FCC spectrum auction system. The potential bidders hired consultants who filed briefs to the FCC and then, after the system was devised, advised their clients on the best methods to use during the auctions. Stanford University professors Jeremy Bulow, Paul R. Milgrom, and Robert B. Wilson, Yale University professor Barry J. Nalebuff, and University of Maryland economist Peter Cramton consulted for major telecommunications firms (O'Toole, 1994).

After considering all the input gathered on the auction process, the FCC decided on an electronic simultaneous multiple-round auction system. This system was chosen because many items' values were interdependent and an asynchronous auction might undervalue particular licenses. "This auction form proved remarkably successful. Similar items sold for similar prices, and bidders successfully formed efficient aggregations of licenses" (Cramton, 1997). The FCC has demonstrated its auction system to representatives of Argentina, Brazil, Canada, Hungary, Peru, Russia, South Africa, and Vietnam. Mexico has licensed this system and has used it in a spectrum auction.

[12]A Nobel Memorial Prize was given to John Nash, John Harsanyi, and Reinhard Selten for work in game theory.

APPLYING RESEARCH ON COGNITION AND LEARNING IN EDUCATION

A number of experts consulted by the panel believe that there is great potential for expanding capitalization on recent research on cognition and learning, which has developed important insights into the functioning of the human mind. This work is ongoing in a number of disciplines, including developmental psychology, linguistics, mathematical logic, philosophy, computer science, and neuroscience, as well as the relatively new interdisciplinary field of cognitive science.

Education is seen as a particularly promising area of application, given the content of the research and the pressing educational problems facing the United States, particularly in early care and learning during the preschool and early elementary school years. Yet research on cognition and learning is not making a measurable contribution to early care and education in the United States today, and even strong proponents of the research believe that prospects for the immediate future are mixed at best. This example illustrates the special challenges of capitalizing on research to address certain pressing national needs.

Research on cognition and learning

The recent wave of research on cognition and learning has its roots in the mid 1950s when a "cognitive revolution" began in American psychology and an interdisciplinary field of cognitive science began to develop.[13] The hallmark of this wave of research is the effort to build understanding of human cognition and behavior from models of unobservable mental constructs related to information processing.[14] Research in these fields is being capitalized upon in a number of areas. Work by Herbert Simon and others underlies developments in artificial intelligence, for example.

Another example that is interesting because it is a clear case of capitalization success is conjoint measurement (also known as conjoint analysis), a technique based on insights from mathematical psychology and psychometrics. R. Duncan Luce, now a professor at the University of California at Irvine, and others developed conjoint measurement during the 1960s.[15] The technique allows for the quantitative characterization of how two or more independent variables affect a psychological dependent variable. This class of problems is recurrent in psychological research. Several years after Luce's work, Paul E. Green of the University of Pennsylvania's Wharton School and others showed how conjoint measurement could be applied to analyzing consumer preferences as an aid to developing and

[13]For an overview of research on cognition and learning, see Bransford et al. (1998). For information on cognitive science as a discipline, see Stillings (1993) (http://hamp.hampshire.edu/~nasCCS/nsfreport.html). Widespread use of the term "cognitive science" and the appearance of distinct educational and research programs has occurred only over the past 20 years.

[14]John Bruer, "President's Statement," John S. McDonnell Foundation homepage (www.jsmf.org).

[15]The seminal paper is Luce and Tukey (1964, p. 1).

marketing new products (Green and Wind, 1975). Over the past several decades, the technique has come to be widely used by corporate marketing departments and consulting companies. Research on cognition and learning also has generated a number of insights that have important implications for education and training.[16]

Research efforts also are being focused on the cognitive development and learning processes of young children. For example, research shows that "naive understanding," the often mistaken prior beliefs and concepts of children, plays an important role in learning.[17] If new or contradictory information is introduced without addressing these prior beliefs and concepts, a child may construct a logical loophole to accommodate the contradiction rather than learn the correct concept.

The implications of this and other research insights for education are far reaching. Experts consulted by the panel believe that new approaches informed by research could significantly improve science and mathematics education in the early grades. In general, approaches informed by research on cognition and learning focus on developing a deep understanding of basic concepts that corrects the naive understanding of children by guiding them through a carefully structured process of discovery. This often implies much less emphasis on memorization of facts and information than traditional educational methods.

Efforts to capitalize

The panel was able to uncover several examples of efforts to apply research on cognition and learning in the classroom during the course of exploring this issue.[18] Research on how children learn mathematics concepts has informed efforts to develop tools for "cognitively guided instruction," focusing on early elementary mathematics.[19] Efforts also are being made to incorporate this improved understanding into training programs for teachers at professional schools of education and associated centers for educational research, often with support from the U.S. Department of Education or NSF. Private foundations play a key role in this area as well. The John S. McDonnell Foundation supports work aimed at applying cognitive science insights to education, and the Alfred P. Sloan Foundation played a catalyzing role in the original development of education and research programs in cognitive science.

A capitalization effort in the area of early science learning is under way at the Institute for Research in Cognitive Science (IRCS) at the University of Pennsylvania.[20] IRCS is one of NSF's Science and Technology Centers [see COSEPUP (1996a)]. A group of professional curriculum developers, classroom teachers, cog-

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[16]For a review of major insights and potential applications, see NRC/CBSSE (1994).

[17]Bransford et al. (1998).

[18]One prominent example is the Learning Research and Development Center at the University of Pittsburgh (www.lrdc.pitt.edu). The examples here are illustrative, and not meant to present a comprehensive picture of developments in this field.

[19]Telephone interview with Thomas Cooney, September 4, 1998

[20]Telephone interview with Christine Massey, September 4, 1998.

nitive developmental and educational researchers, and university scientists is developing, field testing, and evaluating science curricula to meet the developmental and practical needs of children in early elementary classrooms (kindergarten through second grade).

The unit on perception, Science Makes Sense, illustrates the overall approach of this initiative (Massey and Roth, 1997). Rather than utilize the traditional kindergarten approach linking the "five senses" with associated body parts, the IRCS-developed curriculum focuses on how we experience and get information about the world through different modalities. Children are guided through a sequence of carefully structured exercises that isolate various sensory modalities and help them become aware that immediate sensory experience can be incomplete or misleading. This approach addresses the naive understanding of five- and six-year olds, such as the common belief that the color of an object can be determined by touch. Science Makes Sense and other components of the IRCS curriculum are being field tested in Philadelphia elementary schools, with encouraging preliminary results.

Issues and barriers to capitalization

The poor relative performance of U.S. students in international comparative studies of mathematics and science education is well known.[21] Improving education has been a major issue on the U.S. national agenda since the 1983 publication of *A Nation at Risk*.[22] Despite the promise of basic and applied research in cognition and learning to improve educational outcomes, there are several significant barriers that need to be addressed in order to realize this promise. This discussion is meant to be suggestive and illustrative rather than comprehensive and conclusive. A full assessment of these barriers would require a separate study.[23]

1. *Learning how to apply scientific insights requires focused effort.*

The general insights and principles developed from the sciences of cognition and learning do not apply in exactly the same way in all fields of instruction. Thus, to move from controlled laboratory applications to particular educational settings is a major step that often requires focused research. Even where research provides clear and unambiguous direction for applications work, developing and testing concrete approaches for the classroom can be an arduous process. Effects on sustained learning of different approaches may take years to measure.

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[21]The Third International Mathematics and Science Study (TIMSS), which was recently completed, involved collection of data on half a million students from 41 countries, and is the largest, most comprehensive, and most rigorous international study of schools and students ever. The National Center for Education Statistics website is a useful starting point for finding out about TIMSS (http://nces.ed.gov/TIMSS/). The TIMSS results contain no information bearing on the utility of learning research in K-12 education.

[22]Respondents to a opinion poll named education as the issue most likely to influence their voting in the 1998 elections (Balz and Deane, 1998).

[23]An extended discussion of the barriers to knowledge utilization is found in Bransford et al. (1998).

2. Up to now, funding for the necessary focused efforts has been limited.

Research on cognition and learning is funded by agencies such as NSF, NIH, and the Department of Education. The latter agency also funds research on new educational techniques. Although some programs have funded work to apply research insights in educational settings, the amount of dedicated long-term funding is limited. For example, the IRCS effort described earlier benefits from access to funding through NSF's Science and Technology Centers (STC) program. STC funding has a limited duration, however, and it is not obvious how continued work will be supported after STC support ends.

3. Institutional incentives to transform useful research into classroom practice are lacking.

Additional funding may not be enough to change educational decision-making routines. Experience from educational reform initiatives suggests that the most promising efforts involve bridge building between education researchers, scientists, education schools, teachers, and communities. This is inherently difficult because these groups have different incentive and reward structures, and none is tasked with application of research in the classroom as a primary mission. For example, researchers advance their careers through successful publication of their research, which leads to tenure and status in their fields. They are not rewarded for making efforts to apply their research insights in the classroom. Teachers face numerous challenges in the classroom, and may have little time or incentive to learn about new approaches based on research. A lack of clear market signals in education may contribute to this institutional inertia.

4. Other possible barriers could be encountered in disseminating new approaches.

Some of the difficulties encountered in applying research on cognition and learning to the classroom are similar to those encountered in other interdisciplinary fields examined by the panel, such as bioinformatics. These barriers include the lack of dedicated funding sources and institutional structures. The application field of education itself could be the source of additional problems in the future. Even if the barriers discussed above can be overcome and new research-based approaches to early education are developed and tested, additional obstacles may be encountered in promoting the widespread adoption of new methods. Several of the experts interviewed by the panel pointed to the advantages that other countries might have over the United States in areas such as stronger systems for funding early care and education, and a stronger national government role in the education system. It is not clear that other countries are applying research on cognition and learning to the classroom more successfully than the United States, however.

Appendix B

COMMITTEE MEMBER BIOGRAPHICAL SKETCHES

COSEPUP CAPITALIZING WORKING GROUP

GERALD P. DINNEEN (working group chair) was Foreign Secretary of the National Academy of Engineering from 1988 until 1995. He was previously Vice President of Science and Technology at Honeywell Corporation and, from 1977 to 1981, he was the Assistant Secretary of Defense and Principal Deputy Under Secretary of Defense for Research and Engineering. He has had a long affiliation with the Massachusetts Institute of Technology (MIT) since 1953 when he joined the MIT Lincoln Laboratory in Lexington, Massachusetts. He advanced through many positions to become the Director, 1970-77, and concurrently, a Professor of Electrical Engineering, 1971-81. He was elected to the National Academy of Engineering in 1975 and serves on many advisory committees and boards for the National Research Council and in government. He has been elected to the Engineering Academy of Japan, the Swiss Academy of Technological Sciences, and the Royal Academy of Engineering of the United Kingdom.

PETER DIAMOND is an Institute Professor at MIT, where he has taught since 1966. He received his B.A. in Mathematics from Yale University in 1960 and his Ph.D. in Economics from MIT in 1963. He is a member of the Board of the National Academy of Social Insurance, for which he has been President and Chair of the Board. He has been President of the Econometric Society and Vice-President of the American Economic Association. He is a Fellow of the American Academy of Arts and Sciences, a Member of the National Academy of Sciences, and a Founding Member of the National Academy of Social Insurance. He was the recipient of the 1980 Mahalanobis Memorial Award and the 1994 Nemmers Prize. He has written on public finance, social insurance, uncertainty and search theories, and macroeconomics.

MILDRED S. DRESSELHAUS is currently an Institute Professor of Electrical Engineering and Physics at MIT. She has been active in the study of a wide range of problems in the physics of solids, especially topics related to carbon-based materials such as carbon fibers, fullerenes, and carbon nanotubes. Millie was awarded the National Medal of Science in November 1990, was elected to the National Academy of Engineering (NAE) in 1974, and to the National Academy of Sciences (NAS) in 1985, and the Engineering Academy of Japan. She has been a member of both Councils of NAE and NAS, the Governing Board, and has served on numerous committees and as NAS Treasurer from 1992 to 1996. She has served as President of the American Physical Society and of the American Association for the Advancement of Science.

M.R.C. GREENWOOD is Chancellor of the University of California, Santa Cruz, a position she has held since July 1, 1996. As chief executive, Chancellor Greenwood oversees a comprehensive teaching and research institution with combined undergraduate and graduate enrollments of approximately 10,850 matriculated students and an annual total budget of $265 million. In addition to her position as Chancellor, Dr. Greenwood also holds a UCSC appointment as Professor of Biology.

Prior to her UCSC appointments, Chancellor Greenwood served as Dean of Graduate Studies and Vice Provost for Academic Outreach at the University of California, Davis, taught at Vassar College, and served as Associate Director for Science at the Office of Science and Technology Policy (OSTP) in the Executive Office of the President. During 1998, she served as President of the American Association for the Advancement of Science, and also has served on the National Science Board. She received her undergraduate degree at Vassar College and her Ph.D. from The Rockefeller University. Her research interests are in developmental cell biology, genetics, physiology, and nutrition.

PHILLIP A. GRIFFITHS (COSEPUP Chair) has been Director of the Institute for Advanced Study since 1991. He was the Provost and James B. Duke Professor of Mathematics of Duke University from 1983 to 1991. In 1983, he was the Dwight Parker Robinson Professor of Mathematics at Harvard University. Dr. Griffiths, who served as a member of the National Science Board, became a member of the National Academy of Sciences in 1979. He chaired the Board on Mathematical Sciences from 1986 to 1991 and chaired the Commission on Physical Sciences, Mathematics, and Applications in 1992. He was the recipient of the LeRoy Steele Prize given by the American Mathematical Society and the Dannie Heineman Prize of the Academy of Sciences at Gottingen.

J. TOMAS HEXNER is president of Hex, Inc. Mr. Hexner brings an entrepreneurial approach to government and business. He was the business founder of the Genetics Institute and the business catalyst for the founding of Thinking Machines Corp. Mr. Hexner was one of the first Harvard MBAs to focus on economic development and has consulted on privatization, external debt, and the effectiveness of state enterprises.

DANIEL MCFADDEN is Director of the Department of Economics at the University of California, Berkeley. His university experience includes E. Morris

Cox Chair and Professor of Economics at UC-Berkeley, Sherman Fairchild Distinguished Scholar at Cal Tech, and Director for the Statistics Center and Economics Professor at MIT. His memberships include Economic Advisory Panel of NSF, Executive Committee of TRB, President of Econometric Society, Executive Committee Member and Vice-President of American Economics Association (AEA). He was the recipient of the John Bates Clark Medal from AEA and the Frisch Medal, and is member of the National Academy of Sciences.

PAUL M. ROMER studied mathematics and physics as an undergraduate at the University of Chicago and received his Ph.D. in economics from there in 1983. He has been a faculty member in the Department of Economics at the University of Rochester, the University of Chicago, and the University of California, Berkeley. Since July 1996, he has been a Professor of Economics in the Graduate School of Business at Stanford. He is a fellow of the Econometric Society, a research associate of the National Bureau of Economic Research, a Senior Research Fellow of the Hoover Institution at Stanford University, and the Royal Bank Fellow of the Canadian Institute for Advanced Research.

Professor Romer's Ph.D. thesis was the opening shot in a new round of debate about growth and government policy. When he wrote his thesis, most work in macroeconomics focused on government policies that would encourage capital accumulation or fine-tune aggregate demand with adjustments to monetary and fiscal policy. This neoclassical approach to macroeconomics treated scientific discovery, technological change, innovation, and productivity growth as peripheral concerns in national economic policy. New growth theory moves these concerns back toward the center of macroeconomic analysis. It suggests that for a developing country, the most important government policies may be those that determine the rate of technology transfer from the rest of the world. For an advanced economy, the most important policies may be the ones that influence the rate of technological innovation in the private sector.

MORRIS TANENBAUM was the Vice-Chairman of the Board and Chief Financial Officer of AT&T from 1988 to 1991. He began his career at Bell Telephone Labs on the technical staff, held various positions at Western Electric Company, including Vice-President of the Engineering Division and Vice-President of Manufacturing, before returning to Bell Labs in 1975 as Executive Vice President. In 1978, he became President of New Jersey Bell Telephone Company, returned to AT&T as Executive Vice-President, Corporate Affairs and Planning in 1980, becoming the first Chairman and CEO of AT&T Communications in 1984.

WILLIAM JULIUS WILSON is the Lewis P. and Linda L. Geyser University Professor at Harvard University. He was formerly Lucy Flower University Professor of Sociology and Public Policy at the University of Chicago. He is a member of the National Academy of Sciences, the American Academy of Arts and Sciences, the National Academy of Education, former member of the President's Committee on the National Medal of Science, and past President of both the American Sociological Association and the Consortium of Social Science Associations. He was awarded the National Medal of Science in 1998.

OTHER MEMBERS OF COSEPUP

BRUCE ALBERTS (ex-officio), President of the National Academy of Sciences, is a respected biochemist, recognized for his work in both biochemistry and molecular biology. He is noted particularly for his extensive study of the protein complexes that allow chromosomes to be replicated, as required for a living cell to divide. Bruce is a past Chair of the Commission on Life Sciences. He has served on the faculties of Princeton University, and as Vice-Chair and Chair of the University of California, San Francisco, Department of Biochemistry and Biophysics. Being committed to the improvement of science education, he has dedicated much of his time to education projects in San Francisco elementary schools.

JAMES J. DUDERSTADT is President Emeritus and University Professor of Science and Engineering at the University of Michigan. He received his B.A. from Yale University in 1964 and his doctorate in engineering science and physics from the California Institute of Technology in 1967. He joined the faculty of the University of Michigan in 1968 and has served as Professor of Nuclear Engineering, Dean of the College of Engineering, and then as Provost and Vice President for Academic Affairs. He was elected President of the University of Michigan in 1988 and served in that role until July 1996. He received the National Medal of Technology for exemplary service to the nation, the E.O. Lawrence Award for excellence in nuclear research, and the Arthur Holly Compton Prize for outstanding teaching. He has served as Chair of the National Science Board, Chair of the Board of Directors of the Big Ten Athletic Conference, and Chair of the Executive Board of the University of Michigan Hospitals. He also serves as a director of the Unisys Corporation and CMS Energy Corporation. He has been a member of the National Academy of Engineering since 1987, and a member of the Executive Council since 1997.

MARYE ANNE FOX, a chemist and member of the National Academy of Sciences, is North Carolina State University's twelfth chancellor. Before this appointment, Marye Anne was the M. June and J. Virgil Waggoner Regents Chair in Chemistry and Vice President for Research at the University of Texas at Austin. Her research interests include physical organic chemistry; organic photochemistry; organic electrochemistry; chemical reactivity in nonhomogeneous systems; heterogeneous photocatalysis; and electronic transfer in anisotropic macromolecular arrays. Marye Anne currently serves on the Council of the NAS, its Executive Committee, and the Committee on Science, Education, and Public Policy. After U.S. Senate confirmation in 1990 of her nomination to the National Science

Board, she served as its Vice-Chairman (1994-96) and chaired its Committee on Programs and Plans (1991-94). She has served on the Texas Governor's Science and Technology Council, has chaired the Chemistry Section of the American Association for the Advancement of Science, and advises its Center for Science, Technology and the Congress. She has served on advisory panels for the U.S. Army, the Department of Energy, the National Science Foundation, and the National Institutes of Health and on 14 editorial boards, including a stint as associate editor of the *Journal of the American Chemical Society*. She has served on boards of the Texas Environmental Defense Fund, Texas Agribusiness Council, Texas Food and Fiber Commission, W.R. Grace, and Oak Ridge Associated Universities.

RALPH E. GOMORY has been President of the Alfred P. Sloan Foundation since 1989. Following his university position as Higgins Lecturer and Assistant Professor at Princeton, he joined IBM in 1959, becoming Vice-President in 1973, and Senior Vice-President for Science and Technology from 1985 to 1989. A member of both NAS and NAE, he has received the Lanchester Prize in 1963, the John von Neumann Theory Prize in 1984, the IEEE Engineering Leadership Recognition Award in 1988, and the National Medal of Science in 1988, the Arthur M. Bueche Award of the National Academy of Engineering in 1993, and the Heinz Award for Technology, the Economy and Employment in 1998. He was named to the President's Council of Advisors on Science and Technology in 1990 and served until March 1993.

RUBY P. HEARN is Senior Vice-President of The Robert Wood Johnson Foundation, the largest health care philanthropy in the United States. The Foundation has awarded over two billion dollars in grant funds since its inception as a national philanthropy in 1972. As a member of the executive management team, Dr. Hearn participates in strategic program planning with the president and executive vice-president and serves as a special advisor to the president and as the Foundation's liaison within the nonprofit community. Dr. Hearn has had the major responsibility for oversight and program development of initiatives in maternal, infant, and child health; AIDS; substance abuse; and minority medical education. Dr. Hearn received her M.S. and Ph.D. degrees in biophysics from Yale University and is a graduate of Skidmore College. She is a Fellow, Yale Corporation. She served on the Executive Committee of the Board of Directors for the 1995 Special Olympics World Summer games in Connecticut, among others. Dr. Hearn is a member of the Institute of Medicine and its governing Council, the National Academy of Sciences Committee on Science, Engineering, and Public Policy, the Board of Directors of the Council on Foundations, and the Science Board for the Food and Drug Administration, and is also serving on the Advisory Committee to the Director, National Institutes of Health.

PHILIP W. MAJERUS has been Co-Director of the Division of Hematology-Oncology at the Washington University School of Medicine since 1973. He holds concurrent positions as Professor of Biochemistry and Professor of Medicine at the Washington University School of Medicine, as Chairman of the James S. McDonnell Foundation's Program for Molecular Medicine in Cancer Research, as Chairman of NAS Section 41, Medical Genetics, Hematology, and Oncology, and as Chairman of the Board of Scientific Advisors National Heart, Lung, and Blood Institute. He was Chairman of the Searle Scholars Program (1989-1993), President of the American Society of Clinical Investigation (1981-1982) and of the American Society of Hematology (1991). Philip is an NAS and IOM member and is a Fellow with the American College of Physicians, the American Academy of Arts and Sciences, and the American Association for the Advancement of Science. He is on the editorial board of the *Proceedings of the National Academy of Sciences*.

SAMUEL PRESTON became Dean of the School of Arts and Sciences of the University of Pennsylvania in January 1998 and has been a faculty member in Sociology since 1979. He is a scholar of population studies with expertise in technical demography and the analysis of mortality and family structure. He has served twice as Chair of the Penn's Department of Sociology, three times as Chair of the Graduate Group in Demography, and as Director of Penn's Population Studies Center and Population Aging Research Center. Dr. Preston is a member of the National Academy of Sciences and its Institute of Medicine, the American Academy of Arts and Sciences, the American Association for the Advancement of Science, and the American Philosophical Society. Earlier in his career he served as a faculty member at the University of California, Berkeley, and the University of Washington. He was Acting Chief of the Population Trends and Structure Section of the United Nations Populations Division from 1977 to 1979. Dr. Preston holds a B.A. from Amherst College and a Ph.D. in Economics from Princeton.

KENNETH SHINE (ex-officio) is President of the Institute of Medicine and Professor of Medicine Emeritus at the University of California, Los Angeles School of Medicine. He is UCLA School of Medicine's immediate past Dean and Provost for Medical Services. He was Director of the Coronary Care Unit, Chief of the Cardiology Division, and Chair of the Department of Medicine at the UCLA School of Medicine. Dr. Shine has served as Chairman of the Council of Deans of the Association of American Medical Colleges, and was President of the American Heart Association. His research interests include metabolic events in the heart muscle, the relation of behavior to heart disease, and emergency medicine.

IRVING L. WEISSMAN is Karel and Avice Beekhuis Professor of Cancer Biology, Professor of Pathology, and Professor of Developmental Biology at Stanford University. Dr. Weissman was a member of the Scientific Advisory Board, Amgen (1981-1989), the Scientific Advisory Board, DNAX (1981-1992), the Scientific Advisory Board, T-Cell Sciences (1988-1992). He cofounded SyStemix in 1988. He was also Chairman of the Scientific Advisory Board, SyStemix from 1988-1997 and he was a member of the Board of Directors, SyStemix from 1988 to

1997. His main research interests are hema topoletic stem cells, lymphocyte differentiation, lymphocyte homing receptors, and phylogeny of the immune system.

SHEILA E. WIDNALL received her B.Sc. (1960), M.S. (1961), and Sc.D (1964) in Aeronautics and Astronautics from the Massachusetts Institute of Technology. She was appointed Abby Rockefeller Mauze Professor of Aeronautics and Astronautics in 1986. She served as Associate Provost, MIT from 1992 to 1993 and as Secretary of the Air Force from 1993 to 1997. Professor Widnall stepped down from her position as Secretary of the Air Force on October 31, 1997, to return to her faculty position at MIT. As Secretary of the Air Force, Dr. Widnall was responsible for all the affairs of the Department of the Air Force including recruiting, organizing, training, administration, logistical support, maintenance, and welfare of personnel. During this time, the Air Force issued its long-range vision statement: *Global Engagement: A Vision for the 21st Century Air Force,* which defined the path from the Air and Space Force of today to the Space and Air Force of the next century. Dr. Widnall was also responsible for research and development and other activities prescribed by the President or the Secretary of Defense. She cochaired the Department of Defense Task Force on Sexual Harassment and Discrimination.

Since returning to MIT, she has been active in the *Lean Aerospace Initiative* with special emphasis on the space and policy focus teams.

WILLIAM A. WULF (ex officio) is President of the National Academy of Enginering. The former NAE Councillor, Dr. Wulf was AT&T Professor of Engineering and Applied Science at the University of Virginia. He has served as Assistant Director of the National Science Foundation, Chairman and CEO of Tartan Laboratories, Inc., and as Professor of Computer Science at Carnegie Mellon University. Dr. Wulf has been a member of NAE since 1993, and has served as Chair of the Computer Science and Telecommunications Board.

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